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THE JOURNAL OF INTELLIGENT MACHINES

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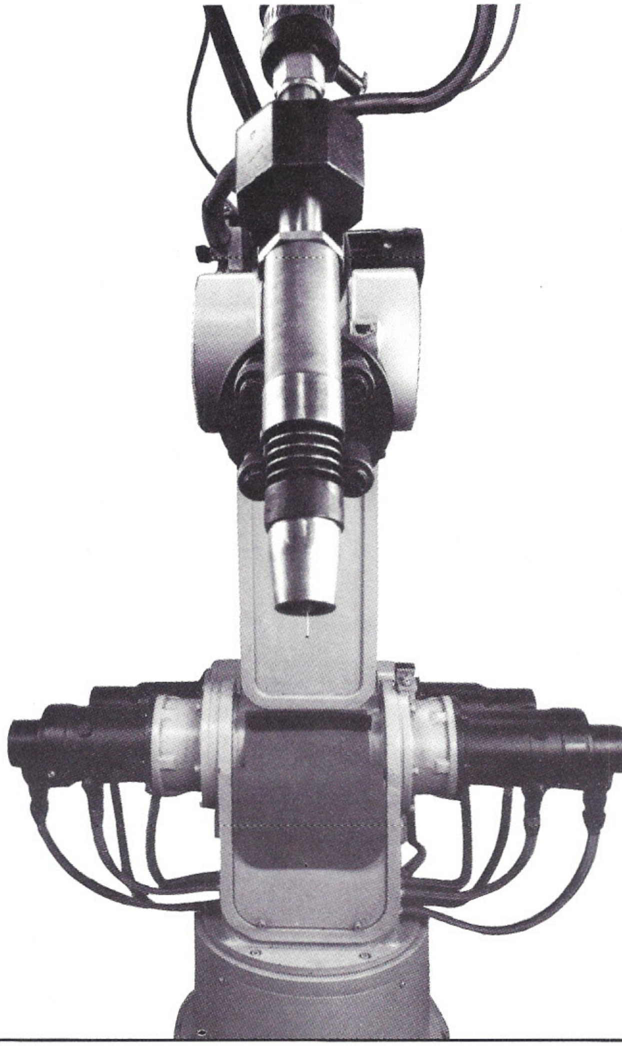

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EDITORIAL

FEATURES

DEPARTMENTS

About the cover: This month's cover photo, provided by Universal Instruments Corp. of Binghamton, NY, depicts the firm's Model 4651A In-line RHyMAS® robots as they automatically and completely populate printed substrates. The system can have as many as 20 processing stations (5 modules) performing multiple functions including circuit verification, solder paste application, and component replacement. See related surface-mount technology articles on pages 5 and 26.

Editorial

What's In A Name?

BY CARL HELMERS

What's in a name? A name is a symbolic tag with both denotative and connotative meaning. With this issue, Volume 8, Number 1, we introduce a new name for our journal: *Robotics Engineering*. The change of title is the culmination of a yearlong process of placing our primary emphasis upon the practical, industrial, and commercial side of the robotics marketplace. This represents a conscious and deliberate change in the direction of our editorial focus, a change that we made to acknowledge our strengths as participants in the forum of technological ideas. Let's examine the history and realities of robotics, and how *Robotics Engineering* fits into this field.

When the journal was founded in 1979, Robotics Age was an appropriate name. During its first three years as a quarterly, and then as a bi-monthly magazine, Robotics Age was the only robotics journal of any consequence. The initial three years focused on all aspects of the field from industrial robotic systems, to the garage tinkerers, to the artificial intelligence researchers' software dreams. After the magazine was revived at the beginning of 1982 with a change of ownership, we continued to address the total robotics picture. As part of covering the broad spectrum of intelligent machine subjects from A to Z, however, we started to be perceived as somewhat of a "hobby" oriented magazine, somehow a less-than-serious contender in the marketplace of system ideas.

Our response to this perception is that there have been and will always be a place for personal robots in areas such as aiding handicapped persons. Lightweight, inexpensive robotic mechanisms coupled to personal computers can do wonders for the blind and the mobility impaired. There is also the field of industrial education in the areas of robotics and automation. Many vendors have contributed to this effort with educational hardware and software simulations of industrial automation systems used to teach automation concepts at levels from the junior college to the graduate engineering schools. Where there is real technology to write about, we will cover these aspects of robotics.

The robot toy market, however, is not the robotics industry of practical intelligent machines even though science fiction speculation is valuable for setting long-term technological goals. We postwar baby-boomers were, after all, brought up on the possibilities of spaceflight, anthropomorphic robots, and the wonders of technology. But science fiction will always be mere speculation compared to the actual incremental evolution of human systems. The "magic bean" of a personal robotics marketplace might be a long time coming, and may actually come as a culmination of the evolution of "smart" appliances. We cannot cut short the process of design evolution—we humans must learn to crawl before we learn to walk, and finally run.

Editorial

To hunt that magic bean of personal robotics was proven a folly in 1984, with bankruptcies, near bankruptcies, and changed plans at all the experimenter-oriented personal robotics companies. What comes in tomorrow's consumer markets still waits for tomorrow's technology—the real world of *Robotics Engineering* is where technology is being advanced today.

As 1986 begins, let's get on with the growth areas of practical robotics and intelligent machines. The goals of the robotics engineering process are practical productivity improvements in the systems used in commerce and industry. There is a practical robotics engineering field, the field of making complex computer controlled intelligent machines do useful, productive work.

In only one applications area, manufacturing, are the subjects wide ranging. We have the automated design arts of software tools used in engineering design and project planning. We have the systems integration problems of making these tools work together with flexible automation, just in time inventories, and smart factories with modern wide-band communications networks. And we have the detail problems of the individual machines, sensors, and manufacturing cells. In the continuous process industries as well as in the discrete manufacturing industries, we're starting to see practical applications of the symbolic programming (artificial intelligence) point of view, as expert systems start popping up as simulated on conventional mini/microcomputers functionally identical to much faster specialized "inference engines."

The engineering problems of intelligent machines are by no means limited to manufacturing. Manufacturing is simply the highest priority task at the moment—other technologically exciting and emminently useful areas of robotics engineering abound at the frontiers of the art. The commercial and military uses of semiautonomous robots are just beginning to be explored. The concept of the semiautonomous computer-controlled system was pioneered with the robotic space exploration probes of the past decades. In today's environment, we see the first practical installations as clean room robots, hazardous environment teleoperators, and autonomous military vehicle technologies. The practical and commercially useful implications of the "chauffeur system," an automatic pilot for an automobile, will ultimately bring about its invention.

As we begin this new year with a new appellation, our editorial goal remains the same: comprehensive technical coverage of the hardware and software systems and solutions needed to accomplish real-world intelligent machine tasks. Our editorial content will address the creative engineering of solutions to the challenges of automation. The *Robotics Engineering* goal is to be the complete guide to the technology of intelligent machine engineering and implementation. ■

Calendar

JANUARY

21–23. **Artificial Intelligence: Current Applications, Trends, and Future Opportunities.** Massachusetts Institute of Technology, Cambridge, MA. Contact: M.I.T. Seminar Office, Center for Advanced Engineering Study, Room 9-335, 105 Massachusetts Ave., Cambridge, MA 02139, telephone (617) 253-7406.

28–30. **Charlotte Tool & Manufacturing Engineering Conference & Exposition.** Charlotte Convention Center, Charlotte, NC. Contact: SME Technical Activities Dept., Society of Manufacturing Engineers, One SME Dr., Dearborn, MI 48121, telephone (313) 271-1500.

FEBRUARY

4–6. **7th International Conference on Assembly Automation.** Zurich, Switzerland. Contact: Conference Manager (ICAA-7), IFS (Conferences) Ltd., 35–39 High St., Kempston, Bedford MK42 7BT, England, telephone (0234) 853605.

11–13. **Orlando Manufacturing Productivity Conference and Exposition.** Orlando Expo Centre, Orlando, FL. Contact: Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121.

MARCH

3–6. **Flexible Manufacturing Systems.** Hyatt Regency O'Hare, Rosemont, IL. Contact: John McEachran, Special Programs Division, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500.

3–6. **Agri-Mation 2 Conference and Exposition.** Chicago Hilton Hotel and Towers, Chicago, IL. Contact: Public Relations Department, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-0777.

12–14. **Artificial Intelligence for the Automotive Industry.** Westin Hotel, Detroit, MI. Contact: Dale Mason, SME Technical Activities Dept., Computer and Automated Systems Association of SME, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500, ext. 375.

17–20. **WESTEC '86.** Los Angeles Convention Center, Los Angeles, CA. Contact: Society of Manufacturing Engineers, One SME Drive, PO Box 930, Dearborn, MI 48121, telephone (313) 271-0023, ext. 328.

18–21. **International Handling & Storage Exhibition—IHSE '86.** National Exhibition Centre, Birmingham, England. Contact: Keith Harris, Trinity Publishing Ltd., Station Approach, Long Lane, Hillingdon, Middlesex UB10 9NR, England.

19–21. **3rd International Conference on Automated Materials Handling.** Metropole Hotel, National Exhibition Centre, Birmingham, England. Contact: IFS (Conferences) Ltd., 35–39 High St., Kempston, Bedford MK42 7BT, England, telephone (0234) 853605.

24–26. **SYSTEMS™ 1, For Integration of Plant Automation Communications and Control.** Chicago Hilton & Towers, Chicago, IL. Contact: Paul Borawski, Assistant Manager, Technical Activities, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-1500.

APRIL

1–3. **Manufacturing Productivity Conference and Exposition.** H. Roe Bartle Hall, Kansas City, MO. Contact: Public Relations Department, Society of Manufacturing Engineers, One SME Dr., PO Box 930, Dearborn, MI 48121, telephone (313) 271-0777.

Flexible Inspection Systems In Surface-Mount Device Production

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Today, for all intents and purposes, marks the end of an entire year of coping with the worst electronics industry recession in the history of the industry, a time of layoffs, overcapacity, red ink, consolidation, and frustration. But recessions can be a powerful blessing in disguise for those who warm up to a challenge rather than freeze in fear. A good change manager finds a recession a terrific time to rethink what is established, to challenge what is assumed, and to explore new ideas.

For printed circuit board production lines, recessions are a time to clean shop, reduce costs, increase quality, and keep what business is out there away from our competitors. But reducing costs while increasing quality in PCB production remains one of the most critical issues facing the electronics industry today. Rising component densities, shorter product life cycles, higher competition, increasing labor costs, and the need for steady yield and quality enhancement all are compelling reasons to explore every viable manufacturing development for its usefulness.

SURFACE-MOUNT TECHNOLOGY: PANACEA OR PROBLEM?

One of the key production changes and important "new" ideas being sustained during this recession is the massive push toward surface-mount technology (SMT). The argument for SMT is well documented: smaller size, higher speed, reduced crosstalk and circuit distortion, lower weight, lower cost, greater reliability, easier and more generic manufacturing, and more efficient use of board geometry using both sides and mixed technology design are among the improvements promised by SMT, and literally hundreds of companies are jumping onto this hard-pitched bandwagon.

But buyer beware! SMT represents a wholly new technology for 95 percent of all PCB manufacturers, and as is the case with any new technology, the first users are still trying to remember what happened to the quality. Ignoring for the time being the current problems associated with a lack of component variety, lack of experienced SMT PCB designers and design tools, and lack of SMT-experienced manufacturing personnel, we are still left with a significant number of severe generic issues that have yet to be resolved, and the bad news is that current techniques to solve these problems just won't work. Let us see why.

QUALITY ROADBLOCKS: THE LIMITATIONS OF CURRENT TEST AND INSPECTION APPROACHES

When we examine the real linchpins of winning in the electronics marketplace, and in particular to win in SMT, we find that quality is *the* major driver. Without it, our field service costs go out the window, our customers go next door, and our business goes south, sometimes permanently. The Japanese have been teaching us this principle the hard way since the early 1970s. Their approach is simple—focus on manufacturing, catch production errors when they happen, reduce costs, and provide the customer with better performance at a better price. The U.S. still has not learned from this example, and Japan is today producing high quality SMT boards for 30 percent of their volume.

Of the U.S. PCB plants we have visited over the last two years, 95 percent are pursuing the same approach they have always followed. In fact, over the years, it has become a buzzword known as ATE—"at the end." We make our boards, we make our mistakes, and we catch them with our testers at the end. In the beginning, we designed functional testers and ran them until circuit complexity choked us. Then in-circuit was introduced as the new ATE. Density grew, double-sided technology evolved, surface-mount appeared on the horizon and in-circuit began to show signs of old age. In parallel, amidst the confusion, we have hired droves of manual inspectors who are expected to find needles in haystacks—and at line speed. To be sure, manual inspection, in-circuit test, and

functional test are necessary and powerful tools. But we ask too much of them, if "at the end" is where we expect to retrieve our mistakes before we pass them on to our customers.

Why? As surface-mount has gained prominence, a whole new wave of inspection and test problems has emerged. Although bare-board errors tend to track those of through-hole designs, assembly and post-solder problems do not. How, when, and to what tolerance do you inspect for component alignment to its pads? What about paste alignment farther up the line? How do you inspect for solder crosses (bridges) beneath J-leaded components? Can contact-based testers handle 25 mil and 12.5 mil pitch testing? How do you test for near opens when electrically they are sound? Current test techniques are proving unreliable in many SMT applications, and manual visual test is proving difficult to impossible. Three-hundred percent inspection is still worthless if the density of 4-sided components is high. Manual inspection in general has proven to be slow and marginally reliable at best, and the finer line geometry leads to operator fatigue and burnout, with an associated cost increase. Retesting is wasteful if the job exceeds the tester's technical units.

Quality is the *major driver. Without it, our field service costs go out the window, our customers go next door, and our business goes south, sometimes permanently. The Japanese have been teaching us this principle the hard way.*

THE EMERGENCE OF FLEXIBLE INSPECTION SYSTEMS AS A PARTNER TECHNOLOGY

In the past year, a new process control technology has begun to fill in the gaps left by manual and ATE limitations and to provide quality control throughout the line instead of at the end. Flexible Inspection Systems (FISs) have emerged as a new approach to quality verification, an optical approach to finding defects in line after each manufacturing step and prior to further value-added processing. FIS goes beyond the capabilities of manual and ATE approaches to eliminate follow-on defects, reduce test/retest time, and increase yields. Although FIS offers the distinct cost advantage of finding simple defects prior to ATE, many of the defects being targeted by FIS manufacturers are also beyond the reach of traditional ATE altogether, offering an additional quality enhancement potential heretofore unknown.

FISs are computer based machines that typically use solid state video cameras and decision algorithms to duplicate the human inspection approach, but with an order of magnitude or more increase in speed and 60 to 100 percent higher reliability. Like human inspectors, FISs are by definition flexible machines able to change over to inspect totally different board types at the push of a button. The machines are trained using preprogrammed, process tolerant heuristics and "good board" matching techniques to inspect for defects in bare-board, loaded-board, and soldered-board production steps. There is no universal, "one system does all" approach and not all the problems have as yet been reliably solved using existing technology. However, the technology has matured to a point where FIS is being increasingly viewed as a mandatory new partner to existing ATE and manual inspection approaches. Let us examine the status of this technology in detail as it relates to each part of the SMT line.

Inspection can occur at a number of places in a typical SMT line, and each area provides various levels of challenge in producing a reliable FIS for that task. The progress and limitations in the technology up until now are detailed below.

Bare-Board Fabrication. In the bare-board area, several inspection requirements exist and are being addressed by a number of manufacturers. The most obvious inspection requirement in PCB manufacturing and the source for close to 50 percent of all PCB manufacturing defects is in the fabrication of the actual bare PCB and its metallic conductors. Pattern shorts, opens, nicks and mouse bites, cuts and cracks, pin holes, channel width expansion or narrowing, and pad size all are possible areas for defects which must be detected. As design rules progress from 10 and 12 mil spaces, through 8 mil and down to 5 or even 3 mil geometries, defects become exceedingly likely, as well as increasingly difficult to discern. Manufacturers including Optrotech, Itek, AEI, Orbot, Testerion/Mania, Matra, Hitachi, Fujitsu, TI, Hughes, AT&T/Lincoln Laser, DITMCO/Integrated Automation, Trackscan, Visionetics, and KLA have introduced or are in the process of introducing bare-board inspection systems. Three other manufacturers—Photo Research, Everett/Charles, and SVS—have introduced similar systems aimed at defects on smaller ceramic hybrids.

Three basic techniques are used in all cases. The design rule technique provides for high-speed measurements to be made that are checked against predetermined geometrical "quality rules." The database or "golden board" technique provides for high-speed pattern comparison of production boards against a known good board. The analytical technique combines qualities of both in selectively performing pattern matches as well as design rule measurements as compared against a statistical model built from production board data.

All techniques have their advantages and disadvantages, and all systems thus far introduced are extremely expensive—between $150,000 and $400,000. The primary limitation or system problem is robustness. Artwork, interlayer, and finished board variation in board color and finish, conductor metal color and finish, and customer layout idiosyncrasies all have a tendency to either abort inspection of intermixed lots or to raise an inordinate level of false flags. While this is currently being approached by suppliers using software based image enhancement, optical filtering, and advanced illumination technology, only a few companies have had enough experience to be moving in the right direction.

Via and Through-hole Inspection. Several of the bare-board pattern inspection systems are also designed to verify presence of vias and/or drilled through-holes. More often, however, detection for presence/absence, location, and diameter of holes is a quality step found farther down in line. In the past, coordinate measuring machines have been used to do sample inspection on identified lots for quality control. More recently, inspection

systems from EOIC, Muromachi Machine Company, and others have been designed to offer high speed 100 percent inspection for various levels of hole quality at line speed.

Solder Paste Screen Print Registration Pre-reflow. Bare boards or substrates for SMT technology today typically are screen printed with solder paste prior to assembly. Paste to pad registration and deposited solder height (quantity and distribution) are the two primary issues for inspection here, and until this time have been addressed using manual inspection sampling. Automatix, ORS, SVS, MVI, IRT, and others are known to be working on parts of this problem with turnkey designs. A different, pre-emptive approach is being tried by some screen printer vendors. AMI, deHaart, and Universial/DEK are known to be working on low-cost, on-the-machine printer alignment vision systems that will properly and quickly align printer to board layout prior to printing, thus eliminating the need to inspect *after* printing (if coverage has been checked).

Issues for optical approaches to this problem revolve around reliability, and for x-ray approaches speed is the current difficulty (Table 1). However, industry watchers believe that other process techniques (solder bumping, electro-plating, conductive epoxy) may supplant current screening techniques, thus eliminating this inspection need.

Table 1
Paste to Pad Approach Comparison

	Visual Alignment On Screen Printer	Optical Inspection Post-Print	X-Ray Inspection Post-Print
ADVANTAGES	• inexpensive ($20K) • pre-emptive • used within the screen printer • very fast	• alignment inspected distribution inspected by height measurement • fairly fast	• distribution inspected for insufficiencies via density measurement
DISADVANTAGES	• coverage not inspected • distribution not inspected	• expensive ($100K) • reactive • floor space • reliability based on process shift unknown	• very expensive ($400K) • reactive • absolute alignment accuracy less than optimal • floor space • slow

Component to Pad Registration Pre-reflow. During or after component placement, inspection is required to verify accurate component to pad placement registration, and there are some who would like component polarity as well. This need has resulted from two development issues:

1. The need for real-time position feedback on placement machines for placing high pinout (25 mil pitch or less) parts onto lands which may shift 8–12 mils in the process; and
2. Part movement after placement due to board handling problems and adhesive flow. Solutions are being approached as a real-time adjustment to the placement machine's using high speed visual decision making (MVI, IR/I, Automatix, Panasonic, TDK, Sanyo, Dynapert, Universal) or can be offered after assembly. Control Automation, Automatix, MVI, American Robot, ORS, and a host of other manufacturers are pursuing the post-assembly market, and it is expected that more will soon join the fray, given the expected growth of this market. The primary issue for all approaches includes inspection speed as well as resolution, where 2–3 mil tolerances for high pinout parts are not unreasonable limits.

Post-reflow Inspection. Again, after reflow, component placement inspection is important. In addition, inspection for tombstoning effects, as well as solder joint integrity (opens, shorts, solder balls, voids, etc.) around the pads are important areas for development. Production-speed, medium-resolution, low-cost, optical approaches as well as low-speed, high-resolution, high-cost, x-ray, and thermographic systems for lab/NDT work have been introduced this past year or are being prepared for market entry (Figure 1). Control Automation, Nicolet, IRT, and a few others are examining approaches to this area's problems.

Benefits. As seen in Table 2, the primary advantage of FIS (in finished, working systems) is far higher throughput with far higher inspection reliability. This in turn leads in many cases to dramatic cost reductions and unusually short payback periods. The often "hidden" cost savings resulting from test, repair, and field service cost avoidance are particularly important here.

THE FUTURE

The industry's current requirements remain virtually unmet due to the nascent stage of the technology. Cost-effective technology in each area is only now emerging. Technical and user interface issues remain the primary stumbling block for most suppliers and users alike. The future will see some minor vision processing hardware refinements (reduction to custom VLSI or gate array solutions) which will drop the already low current base hard-

	Optical	X-Ray	Thermographic/Laser
Inspection Capability	Opens/Shorts/ Alignment	Opens/Shorts/ Alignment, Solder Balls, Voids, Paste Quantity	Opens/Shorts/Hot Spots
Speed	⩾200 Leads/ Second	⩽75 Leads/ Second	⩾200 Leads/Second (In Theory)
Reliability	High	High	Medium
Status of Technology (Auto. Systems)	Existing	Experimental	Experimental
Cost	Approx. $120K	Approx. $500K	Approx. $500K
Use	Production	Lab /NDT	Lab /NDT

Figure 1. Post solder approach comparison.

ware prices. But this is not a primary market constraint today. Sheer technology is no longer a concern.

The vast majority of the refinements will occur in the applications area, as image processors are combined with peripheral equipment into turnkey system packages aimed at specific niches. Exotic lighting or imaging techniques may play a hand (infrared, ultraviolet, and x-ray), but a majority of the work will involve software enhancement (perhaps later reducible to hardware for speed) that allows for clever solutions to currently unsolved problems, and provides for simple interface to allow changes in most current offerings. The market for this important technology will continue to be limited to innovative users.

Table 2
PCB Flexible Inspection Systems Benefits

QUALITY ENVIRONMENT	
• FEWER PROCESS ERRORS	
• FEWER MANUAL INSPECTION MISTAKES	
COST REDUCTION	
Automatic Throughput:	5-10 Times Manual Operator Speed
Reliability:	30%-50% More Reliable And Repeatable
Yield:	5-10% Yield Enhancement
Test Avoidance:	5-10% Test Equipment And Labor Cost Avoidance
Repair Cost Avoidance:	Post-Solder Repair Costs 2-5 Times Greater Than Pre-Solder Costs
Field Service Avoidance:	Field Repair Costs 10 or More Times Greater Than Post-Solder Costs
RESULT	
Enhanced Quality Image — Fewer Problems With Equipment On Customer Premises	

EVALUATING VENDORS: THE ISSUES TO PURSUE

As with any new technology, unsophisticated users can be taken by surprise by vendors who promise much but deliver little. Surprises and mistakes can be avoided by being aware of several critical issues and asking the right questions. Many of the same questions you have always asked ATE vendors, and many of the same problems you have found over the years, will evidence themselves in your exploration of FIS:

- Hardware—is *not* an issue, as over 200 vendors world wide now sell roughly equal vision boxes (some faster, some slower) performing roughly the same basic vision tasks. Don't be overly impressed by pixel rates, convolution algorithms, and parallel processing. If the machine can't reliably inspect your printed circuit boards to your satisfaction while you're watching, go elsewhere.
- Lighting and Optics—*is* one of the two absolutely critical issues. Lighting must be absolutely constant across all of your board to produce reliable results. Board peripheries, multiple board colors, solder plating variation, and component color variation can be particularly troublesome to many vendors.
- Application Software—is the second

Circle 33

absolutely critical capability area. This involves two subsets.

1. Environmental Tolerance—software "ranging" to compensate for warp, color, sag, finish, size pattern registration, and solder finish variation must be included in the system to allow it to examine *all* your board types, reliably, from batch to batch. Make sure you ask to see these abilities demonstrated on *your* boards; several current users of immature technology now wish they had.

2. Board Teaching/Set-up—set-up time and operator ease of use can make the difference between go and not go, and your second and third shift operators must know how to run the equipment. Ask to teach a board and have it inspect reliably. Don't buy until you're satisfied with this capability issue or you will regret it later.

FEATURES

- Speed—is important for your throughput requirements. Make an apples-to-apples matrix to compare speeds you've had demonstrated on *your* boards. Don't believe specs yet—many are still mostly hype.
- CAD Downloading—the ability to CAD download inspection locations reduces 60–80 percent of your teaching time and is a tremendous advantage.
- Factory Networking—board data uploading and downloading to/from hosts and repair stations is critical in packaging a turnkey system.
- In-line Capability—a self-contained transfer system allows you to run in line, increase throughput, and reduce operator intervention.
- Statistical Error Analysis—a comprehensive error tracking and trend analysis package is handy to track your process and back up management reports.

When you go out exploring FIS alternatives, look for these capabilities and ask to see them demonstrated on your boards with your help, so you can compare the status of the machine as far as production readiness. As a final test, ask how many units the supplier has in the field, talk with at least two to three reference sites, and visit one if possible to see a system in operation and talk to a user. Face to face interaction yields much more reliable information than phone recommendations. When all is said and done and you have reviewed all the capabilities and features, ask about the price tag for the full set of operating capabilities you want, and run an ROI to check for justification. Technology is useless to you if you can't cost-justify it.

Control Automation's InterScan Family of Turnkey PCB Inspection Systems are examples of turnkey systems that work. Each of the systems is push button controlled and menu driven, and is designed for particular tasks within the pre-wave-solder through-hole inspection and post-wave SMT inspection niches. Each system is designed for both off-line and in-line operation, and has embedded in it environmental calibration routines, statistical data and analysis algorithms of operation, and redundant hardware and software modules to guarantee the highest possible reliability. The systems are low-cost, and designed for a one-year or less payback on the average PCB line. With over 40 systems installed in the company's first year, dozens of reference accounts and sales, and installation and service provided by Control Automation's partner, Universal Instruments Corporation, the InterScan systems are established, market leading products.

CONCLUSION

FIS is rapidly being accepted in the SMT and PCB industry as a necessary, viable and highly cost-effective addition to the quality tools currently available to PCB production and test organizations. Several applications have seen successful and reliable products introduced, and more are on the way. A knowledge of your defect inspection priorities and a careful vendor evaluation will result in a successful installation of a new, but proven, technology. FIS promises to shake up the industry and provide a fresh approach to cost reduction, quality enhancement, and winning in the marketplace.

Scott T. Jones is Vice President of Marketing for Control Automation.

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Artificial Intelligence—The Achilles Heel of Robotics and Manufacturing

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Surveying the state of manufacturing technology, of which robotics is only a part, albeit an important part, an automation expert cannot help noticing gaps that represent weak links in the manufacturing chain. CIM (computer integrated manufacturing), while a much heralded technology, represents a goal to be attained rather than a reality; integration is precisely what is lacking. Making robots and other systems needed in manufacturing more intelligent will not in itself lead to a higher degree of automation. To achieve this, technological solutions are needed that enable us to forge stronger links in the manufacturing chain. This metaphor is, I believe, appropriate, for it is the linkages in manufacturing that are resisting automation. These linkages represent the transitions between different phases which demand human information processing that are presenting the greatest challenges to automation and will continue to do so for the foreseeable future. Artificial intelligence (AI) is the principal technology resource for resolving these bottlenecks. This writer's contention is that it is not sufficient for AI to be integrated into isolated systems such as robots, but that intelligence must be distributed at strategic points throughout the manufacturing system. Especially important is intelligent communication between different phases of the entire operation. These points will be taken up in due course.

In manufacturing automation, as with many human activities, we have taken the path of least resistance, i.e., we have been automating what we know how to, rather than what really needs to be automated. The difficulty starts right at the beginning when designs are produced on CAD (computer aided design) systems. While CAD systems have given great freedom to the designer, they have not increased manufacturing productivity to any significant degree. A fundamental weakness of CAD systems is their lack of manufacturing knowledge. In addition, representations used in CAD are strongly graphics oriented, and are much too weak for generating manufacturing processes. The key is representations. CAD systems typically represent objects as arrays of numbers, representations which present considerable difficulties in turning such designs into processes for production or manufacturing. Also, designs produced on CAD frequently fail, simply because the designer working with the CAD system is not fully aware of the constraints of manufacturing. This lack of manufacturing knowledge leads to a lot of unnecessary work for production planning and control personnel who will need to examine and reject designs for lack of manufacturability. Thus, CAD systems can create bottlenecks in manufacturing. The reasons are partly historical. CAD technology has been pioneered by the defense aerospace industry, an industry in which design is paramount; it is the design which is sold to the customer and the customer pays for the installation of the manufacturing capacity. Consequently, CAD systems were originally developed to gain a competitive edge in selling designs, there being little competition for the manufactured product—a situation vastly different from the one prevailing in the manufacturing industry. Thus, it appears that CAD technology is solving problems for the aerospace industry but is leading to manufacturing bottlenecks in other industries, such as the automotive industry. The bottlenecks are especially troublesome during the transition from design to manufacturing. If the Japanese seem to experience

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less difficulty in this process than we do in the U.S., I believe it is because in Japan manufacturing people are involved quite early in the design phase. This enables them to make a smoother transition from design to manufacture.

A simply stated, but by no means simple solution, is to incorporate manufacturing knowledge into the CAD database itself. This calls for the use of much more powerful representation schemes in CAD. This is a prime candidate for AI technology, for AI researchers have developed an extremely rich range of representation schemes. Summarizing our discussions so far:

- Representations used in CAD systems are much too weak, and often lead to designs which cannot be manufactured. Representation methods used in AI can go a long way toward enabling much more powerful CAD systems with knowledge bases than those with only data bases.
- CAD systems lack knowledge about the subsequent phases of operation. Once again, AI methods offer the tools necessary for integrating such knowledge into the CAD knowledge base.

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The key requirement for manufacturing automation can be stated quite simply: from a given design, which is a static piece of information, we should be able automatically to generate a sequence of manufacturing processes that are inherently dynamic. In particular, it should be possible to generate the following:

- Processes needed to manufacture the designed product
- Tool paths, cutting speeds, time standards, and other necessary parameters
- The sequence of machining and other operations to be performed
- A schedule of the routing of the parts on the factory floor and the necessary numerical control programs for the various machines in the sequence
- Robot motion sequences to be executed at each robot station, and control and communication between various machines, robots, conveyors, and so forth

I hope this clarifies the point made earlier that the main difficulty to be overcome in achieving CIM is automation of transition operations. Before looking at the AI technology in greater detail, let me enumerate the tools or resources that it provides.

- Procedural representations. AI languages make no distinction between data and programs. This enables programs to be manipulated as ordinary data elements, and also permits data to behave like programs. For example, in the AI language LOGO graphical information can be represented as procedures for executing motion sequences.
- Object-centered programs. Since AI languages treat data and programs in the same way, it is possible to assign programs as values of variables. This

makes it possible for objects to carry several procedures as attributes. For instance, it is possible to make an object carry all the programs needed to manufacture it.

- Rule based programs. One of the major applications of AI is solving problems in specialized areas such as medicine, organic chemistry, and molecular genetics. These are programs which reason, using rules and symbolic information, and are known as expert systems. They are likely to play a major role in many application areas, including manufacturing.
- Data driven programming. AI programs are frequently data driven, i.e., the sequence of instructions (usually rules) executed by the program depends upon the input to the program. This means that a particular program can follow different semantics for different data inputs.

While all these are available to one interested in applying AI methods to practical problems, only expert systems are capturing the attention of workers in other fields. While I have no intention of underestimating the importance of the powerful technology of expert systems, it nevertheless appears to me that manufacturing experts are focusing on the superficial novelty of such systems to the exclusion of other resources of AI technology and are hoping that expert systems will prove to be a panacea. Unfortunately, reality will prove to be quite different. What is needed is a pragmatic examination of the bottlenecks and a determination of the approaches and technologies needed for their solution. Previous experience with AI problem solving has shown that representations are the key. It will be no different in robotics and manufacturing.

ARTIFICIAL INTELLIGENCE IN THE FACTORY

As noted earlier, the key to computer integrated manufacturing is the distribution of intelligence at strategic points throughout the manufacturing process. Further, there needs to be intelligent communication between different systems. An example of intelligent communication is for a robot to change its own control program in response to a change in the speed of the conveyor carrying the parts to the robot. A robot is, of course, only one of many computer-controlled systems in a large manufacturing operation. To be able to reprogram the entire operation "on the fly" with a minimum of interruption would be a significant advance since it would permit changing the product line without having to shut down the whole plant to reprogram the subsystems individually. Consequently, to be able to develop the entire manufacturing plan and all the necessary software at the CAD workstation itself and then download it to the machines on the factory floor would have tremendous implications for productivity. This again suggests that we need uniform and powerful computer representations for designs, plans, and manufacturing processes, to facilitate the transition from one phase to the next. This scenario, in addition to generating major productivity gains, is likely to lead to far-reaching changes in the way we work, and in the structure of management organizations themselves. In the long run, the impact of AI and automation is likely to be greater on the management and organizations than on the factory floor.

Less reliance should be placed on the "structure" of organizations that are likely to change, and more should be devoted to the education of individuals and groups making up the organization.

Robotics technology as it exists today exhibits several glaring shortcomings that need to be remedied before totally automated plants can be built for anything but the simplest of products and the flexibility be provided to change the product mix, or even the product itself, with a minmum of interruption. Since we are concerned here with the relevance of artificial intelligence, I will discuss only the cognitive aspects of robotics, as opposed to issues of mechanical design and servo control.

An unrecognized weakness of the current generation of robots is that they have to be programmed individually; a robot program developed from a mathematical model, when loaded onto a robot, usually does not produce the motion sequence as planned and predicted in deriving the program. This means that each robot is an "individual," and programming a robot is somewhat akin to teaching.

This has several major ramifications. First, the programs developed for one robot cannot be used on a different robot to perform the same task. The situation is similar to having some software for personal computers producing different answers on different computers for the same input. Such unpredictability clearly precludes off-line programming in any real sense. This means also that there can be no "application software" that can be used on a large number of robots. One conceptually appealing solution is to use AI to provide the robot with knowledge at different levels of abstraction so that it is aware of the generic nature of the task as specified by the application, as well as the necessary modification to the program as demanded by its own idiosyncrasies. This calls for each robot to be provided with a certain degree of "self awareness." In theory, this can be done by providing each robot with a "self awareness package" consisting of a database of its performance in executing a few basic motion elements. It would then be the robot's responsibility to express the desired application, as specified by the application package, in terms of the basic motion sequences in its database and to adjust the parameters accordingly. As can readily be seen, we are speaking of quite sophisticated AI capability, in effect requiring the robot to generate plans to adapt itself to new tasks as they are assigned. This leads us to a second major weakness of present-day robots.

Robot programming languages, which provide the link or the communication between the task and control, are very low level, typically being at the robot joint level. Each task must be analyzed in excruciating detail and expressed in terms of individual joint motions. This "task planning" is the responsibility of the robot programmer.

AI has the potential for automating many of the task planning functions. Clearly, the development of task level languages is closely related to the problem of making a robot generate its own plan. Any research done in obtaining representation and rules for generating plans will likely be of benefit in both of these areas. Some previous research into plan generating systems has used a branch of mathematical logic known as predicate calculus. While some of that research is quite impressive,

predicate calculus, as a formalism, seems to be inherently unsuitable for applications in situations where numerical accuracies and calibration and tolerance requirements are central, as they invariably are in robotic applications.

Finally, a third basic problem with robots today is their inability to adapt their behavior to changes in the environment. This difficulty is usually overcome by careful engineering of the environment, an approach clearly not feasible in applications where the environment cannot be controlled. For instance, one can cite numerous applications in hazardous environments, such as outer space, the ocean floor, off-shore platforms, polar regions, and so forth, where robots could be justified on both economic and human safety grounds if the technology were available. Computer vision technology is showing considerable promise for robotic applications such as assembly, arc welding, inspection, and several others impossible without vision. It is necessary, however, to keep computer vision technology in perspective, for vision systems are fairly specialized and some fundamental questions on representation and programming have to be answered before we can speak of "robots with vision" in any meaningful sense. Once again, the problem seems to be one of transitions, namely, the transition from a "low level" image consisting of an array of reflectance values to a "high level" symbolic description of the contents of a particular scene.

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The use of AI to enhance the intelligence of robots does not, by itself, lead to productivity gains in manufacturing. At least as important are obtaining powerful representations to facilitate transitions from one phase to the next, the distribution of intelligence at strategic locations in the entire operation, and communication between various systems and subsystems. Further, both the organization and the humans making up the organization will have to make the transition to both a new structure and to new styles of work, which is likely to prove the greatest challenge of all.

TECHNICAL AND HUMAN CHALLENGES

We have been looking at the potential role of AI in resolving bottlenecks in manufacturing automation from the perspective of the factory floor and with particular emphasis on robotics. One change that seems to be an inevitable result of computerized automation is that manufacturing will shift from a "materials based" to an increasingly "knowledge based" activity. Herein lies the importance of AI, for AI is a prime technology resource for the creation and manipulation of knowledge. But the impact of AI is likely to go far beyond the factory floor and to permeate the functions and activities of information workers such as managers, engineers, planners, and all the others who make up

a productive organization. Clearly, transformations of this magnitude are bound to present challenges at all organizational levels. The question naturally arises: how best to make the transition to an organization dominated by the processing of information and knowledge? We can here attempt to address some of these questions. It is to be noted that the conclusions to be presented are by their very nature bound to be somewhat speculative, and should be regarded as the result of "informed guesswork."

Since the issues involved are quite complex both individually and in relationship to one another, it is convenient to focus on the following factors to better understand the global implications of these technologies.

- Technological Factors. Artificial intelligence as a field is extremely broad in its scope, but only two aspects are germane to this discussion, namely, Knowledge Based Systems and Intelligent Communication.
- Management Factors. Integration of sophisticated computer and communications technologies, including knowledge based technologies, into an organization requires reorientation at both the individual and the organizational levels. In particular, it can be expected that frequent reeducation of personnel and reorganization of departments and other groups will be necessary. Perhaps the greatest challenge for the senior management will be to foster a corporate culture in which reeducation, career changes, and frequent reorganizations are accepted as a way of life.
- Operational Factors. Management and control in the face of so many changes will require imagination and forethought. There are at least two considerations that must be borne in mind. First, less reliance should be placed on the "structure" of organizations that are likely to change, and more devoted to the education of individuals and groups making up the organizations. The guiding principle for choosing a particular structure for an organization should be optimizing the flow and sharing of knowledge.

Technological Factors: Myths and Reality. Before one can study the impact of knowledge based (or AI based) technologies on the operations of any organization, it is essential to place technological advances in their proper perspective. Because of the large amount of publicity being generated by the popular media, as well as by the AI companies, a picture of the emergence of something totally new and profound is being foisted on the public. While it is not my intention to underestimate either the power or the importance of knowledge based technologies, the reality is that AI is a natural evolution in computer applications, with its own specialized formalisms and scope. With a few notable exceptions, most knowledge based systems today are isolated systems, demonstrations of such technologies, potential rather than real-world application systems. The simple fact that computer vision systems, also the result of AI research, are finding increasing application in manufacturing suggests a similar evolution for applications of other branches of AI as well. As with vision systems, systems based on knowledge based technologies can find fruitful applications in industry only when used in conjunction with other systems. In other words, for knowledge based technologies to realize their full potential and make their contribution toward manufacturing automation, systems integration will be the key.

While most of the attention is being given to the technological promises of knowledge based technologies, the major challenges in exploiting their potential will prove to be managerial, for technology can advance no faster than our ability to manage it.

From the applications point of view, AI can be seen to consist of methods that can lead to the design of two kinds of systems:

1. Problem solving and decision making systems which process symbolic information, also known as expert systems.
2. Systems capable of intelligent communications, namely, vision systems and speech and natural language understanding systems.

At present, AI systems are quite specialized; they use domain specific knowledge to solve individual problems in that domain. In general, regardless of the type of AI technology used, the chances of success are better if one attacks narrow problem domains. This is not necessarily a disadvantage, because one can establish a distributed network of communicating knowledge based systems with each system working within its own specialized domain but communicating with other systems under the supervisory control regime of a supersystem. Human interface and management control should preferably be via natural language man-machine systems. In fact, this might be the only way in which a large organization can gain the productivity advantages of integrating knowledge based technologies throughout the organization and at the same time maintain management control. The need for systems integration is self evident. Everything in this scenario is probably within the scope of AI technology as it exists today.

The scope and the state of applications of the AI technologies can be broadly summarized as follows:

- AI technology is not new. Methods being used in knowledge based systems go back a decade or more. It is the dramatic drop in the cost of computing that is making it feasible and cost-effective to produce systems based on such technologies.
- Commercial applications of knowledge based methods will come about only through systems integration. While there are AI software and services companies attempting to address this market, they lack the necessary applications base and the systems integration capability to produce serious applications.
- While expert systems are getting the major share of attention, it is likely that intelligent communication will prove to be equally important in commercial applications of knowledge based technologies. One application such technology promises is in establishing communication between incompatible CAD systems.

Management Factors. While most of the attention is being given to the technological promises of knowledge based technologies, I believe the major chal-

lenges in exploiting their potential will prove to be managerial, for technology can advance no faster than our ability to manage it. My observations are based on personal experience in efforts at establishing knowledge based organizations, initially unsuccessful, and later, relatively successful, at a high technology company and the NASA Mission Control Center. In addition, I have been either involved with, or a close observer of similar efforts at other organizations. The lesson I have drawn is that organizations attempting to "get into" knowledge based technologies tend to overestimate the technical difficulties and underestimate the management challenges. Many professionals will view this new technology as a threat. The following factors must be carefully weighed in planning for knowledge intensive organizations, or attempting a transition to such an organization:

- Confusion Factor. A major source of error is the prevailing confusion between technical and management problems. Many of the knowledge based systems were products of university research and there is a widespread tendency to follow not only the methodology, but also the organization of university research labs. While this might be reasonable in a corporate research lab, it is entirely inappropriate for an organization involved in practical applications. What are technical problems in a laboratory frequently become managerial problems in systems engineering.
- Threat Factor. The perceived threat is two-fold. First, there is the threat of a profession's becoming obsolete due to a new technology. Second, there is the threat of organizational changes forcing new ways of doing things. Since knowledge based technologies impact information processing professions, these threats will be felt by both managers and professionals, especially at the middle level.
- Personnel Factor. It is neither feasible nor desirable to build a knowledge based technical capability primarily through recruitment. First, it is much easier to take existing personnel with applications knowledge and experience and train them sufficiently in AI, which will enable them to turn their expertise into expert systems, than it is to bring in outsiders and familiarize them with the problems and operations. Second, it is good for employee morale, since anyone going through such an experience will have acquired a new and valuable skill. Education is the single most important tool. At present, it is unrealistic to expect outside consultants to produce useful AI based application packages. Building expert systems requires detailed knowledge of the application.

Organizations attempting to "get into" knowledge based technologies tend to overestimate the technical difficulties and underestimate the management challenges.

Operational Factors. We have so far outlined the technical aspects and the management problems in developing an organization built on knowledge intensive technologies. We shall now look briefly at how to achieve the necessary transformation in an existing organization. While new technologies bring new opportunities, if the right leadership does not exist the problems are likely to outweigh the potential benefits. This leadership is less a matter of a few superstars than it is the diffusion of knowledge, awareness, and leader mentality at all levels of the organization. It is the responsibility of the top management to foster such a culture. The major challenge will be adaptation to change, both at the individual and the organizational levels. Challenges and opportunities exist at both levels:

- Most individuals will have to make several career changes during their professional lives. For instance, a person who is an expert in a specialized field, and whose expertise can be turned into an expert system should be given the opportunity, through retraining, to be the expert system designer. This approach is good for employee morale, and instead of becoming a victim of obsolescence, the employee acquires a valuable new skill of both personal and organizational benefits.
- Similar opportunities should be provided to all professionals whose careers are threatened by the infusion of knowledge based technology; demand for education within organizations will continue to increase.
- This education need will be quite focused and unlikely to be met by universities, which are too slow to respond to changes in the needs of the outside world. New opportunities will thus be created for retrained professionals, some of whom might become education professionals within the organization, helping others make similar transitions.

Organizations will also have to change with the changes in technologies and market conditions:

- Organizations should place less reliance on "structure" than on function to ensure an optimal exchange and flow of knowledge.
- The effectiveness of any organization will depend upon the education of individuals at all levels, so that they understand the underlying reasons for structural changes.
- In making organizational changes, the guiding principle should be to optimize the flow and sharing of knowledge.

In summary, the major benefits of AI and knowledge based technologies will come about only through systems integration. The major impact of these technologies will be to bring changes in the professions and management. The principal resource for meeting these challenges is education at all levels of the organization.

For Further Reading

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Geometry of the Robotic Workplace and the Homogeneous Representation

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In spite of the fine work available (1-9), the geometry of robotic position and movement is confusing to many. The problem seems to lie in the distinction between a point and a vector, the meaning of a plane in three-dimensional space defining the surface of an object, the definition of a line, etc. In short, there are confusing differences and/or omissions in the work of various authors. The weakest area is in the use of planes, since their use seems inhibited; it is as if what has been derived is not universally applicable. However, the extensive use of planes (10, 11) leads to a simpler specification of robot position and permits the mathematics of imaging (and so remote control) to be unified.

A vector has direction and length but not location. To define the position of a point in space we need four quantities, although only three are independent (7, 12); it is possible to use the fourth quantity by implication, but this will be shown to be troublesome. A plane is often defined from the vector cross product (13), but the result has orientation without position. A plane is defined in the homogeneous representation as $p = [a\ b\ c\ d]$, and its position in space is fixed; only three of these quantities are independent. A point or a plane specified by four quantities (a four-tuple) is said to be in the homogeneous representation. Point **u** in three-dimensional space is then defined as $[x\ y\ z\ s]^t$, where s is any finite number and superscript t denotes transposition; if s is zero, then **u** is considered a vector.

The homogeneous representation derives its name from its ability to specify position in three-dimensional space without resort to a separate restriction equation. The transformation produced from the four-tuples produce 4 x 4 matrices called homogeneous transformations that can provide for every kind of transformation (translation, rotation, scaling, and imaging) within a single matrix (7). It will be shown that this is sometimes inconvenient and is avoided.

POINTS

A point in three dimensional space is

$$\mathbf{u} = \begin{bmatrix} x \\ y \\ z \\ s \end{bmatrix} \equiv \begin{bmatrix} \alpha x \\ \alpha y \\ \alpha z \\ \alpha s \end{bmatrix} \equiv - \begin{bmatrix} \alpha x \\ \alpha y \\ \alpha z \\ \alpha s \end{bmatrix}$$

The distance of the point from the origin is $\sqrt{x^2 + y^2 + z^2}/s$, so $[x\ y\ z\ s/2]^t$ is twice the distance from the origin as $[x\ y\ z\ s]^t$. Without loss of generality we will use $s = 1$ when we specify points.

The distance between two points $\begin{bmatrix} u_x \\ u_y \\ u_z \\ 1 \end{bmatrix}$ and $\begin{bmatrix} v_x \\ v_y \\ v_z \\ 1 \end{bmatrix}$ is $D = \sqrt{(u_x - v_x)^2 + (u_y - v_y)^2 + (u_z - v_z)^2}$ (1)

LINES

A straight line in three-dimensional space can be defined parametrically as $\mathbf{u} + \alpha(\mathbf{v} - \mathbf{u})$ where **u** and **v** are points on the line. The intersection of two lines in two-dimensional space will always occur provided the two lines are not parallel. In three-dimensional space it is unlikely that two lines will intersect due to round-off or experimental error; an averaging scheme is used to estimate the most likely point of intersection.

Given line $u+\alpha(v-u)$ and point $[x\ y\ z\ 1]^t$, the distance of a point on the line from this point is

$$D^2=\{(1-\alpha)u_x+\alpha v_x-x\}^2 + \{(1-\alpha)u_y+\alpha v_y-y\}^2 + \{(1-\alpha)u_z+\alpha v_z-z\}^2$$

and $\dfrac{\partial D^2}{\partial \alpha} = -2u_x\ \{(1-\alpha)u_x+\alpha v_x-x\}\ -2u_y\{(1-\alpha)u_y+\alpha v_y-y\}\ -2u_z\{(1-\alpha)u_z+\alpha v_z-z\}\ =0$ at a maximum or a minimum.

$$\text{Thus}\quad \alpha=\frac{u_x^2+u_y^2+u_z^2-u_xx-u_yy-u_zz}{u_x^2+u_y^2+u_z^2-u_xv_x-u_zv_z} \tag{2}$$

In a similar manner the minimum distance between two lines can be found.

PLANES

Planes $p_1=[a_1\ b_1\ c_1\ d_1]$ and $p_2=[a_2\ b_2\ c_2\ d_2]$ are parallel if $a_1=\alpha a_2$, $b_1=\alpha b_2$, $c_1=\alpha c_2$ for any non-zero α; planes p_1 and p_2 are the same if additionally $d_1=\alpha d_2$. Although four quantities define a plane, only three and any three of them are independent. In dealing with robot joints it is convenient to normalize the length of the vector partially defining the plane to unity, i.e. $a^2+b^2+c^2=1$, and then refer to the plane as normalized.

Vector $[a\ b\ c]^t$ is orthogonal to the plane $[a\ b\ c\ d]$, so the angle (minimum) between two planes $[a_1\ b_1\ c_1\ d_1]$ and $[a_2\ b_2\ c_2\ d_2]$ is given by the cross product

$$\sin\theta=\begin{bmatrix}a_1\\b_1\\c_1\end{bmatrix}\times\begin{bmatrix}a_2\\b_2\\c_2\end{bmatrix}=\begin{bmatrix}0&-c_1&b_1\\c_1&0&-a_1\\-b_1&a_1&0\end{bmatrix}\begin{bmatrix}a_2\\b_2\\c_2\end{bmatrix}=-\begin{bmatrix}0&-c_2&b_2\\c_2&0&-a_2\\-b_2&a_2&0\end{bmatrix}\begin{bmatrix}a_1\\b_1\\c_1\end{bmatrix}=\begin{bmatrix}b_1c_2-c_1b_2\\c_1a_2-a_1c_2\\a_1b_2-b_1a_2\end{bmatrix} \tag{3}$$

Points and Planes. A point $u=[x\ y\ z\ 1]^t$ lies in the plane $p=[a\ b\ c\ d]$ if $pu=0$, i.e. $ax+by+cz+d=0$. The plane will intersect the z axis at $x=0$, $y=0$, for which $cz+d=0$, or $z=-d/c$. Similarly, the plane will intersect the x and y axes at $-d/a$ and $-d/b$ respectively. If $d=0$ the plane intersects the origin. Plane $[1\ 0\ 0\ 0]$ is the y-z plane passing through the origin.

Three points $[u_x^i\ u_y^i\ u_z^i\ 1]^t$, $i=1$, 2 and 3 can define plane $p=[a\ b\ c\ d]$ from the cross product of the two vectors formed as the difference between two different pairs of points, i.e.

$$\begin{bmatrix}a\\b\\c\end{bmatrix}=\begin{bmatrix}u_x^1-u_x^2\\u_y^1-u_y^2\\u_z^1-u_z^2\end{bmatrix}\times\begin{bmatrix}u_x^1-u_x^3\\u_y^1-u_y^3\\u_z^1-u_z^3\end{bmatrix}=\begin{bmatrix}(u_y^1-u_y^2)(u_z^1-u_z^3)-(u_z^1-u_z^2)(u_y^1-u_y^3)\\(u_z^1-u_z^2)(u_x^1-u_x^3)-(u_x^1-u_x^2)(u_z^1-u_z^3)\\(u_x^1-u_x^2)(u_y^1-u_y^3)-(u_y^1-u_y^2)(u_x^1-u_x^3)\end{bmatrix} \tag{4}$$

Geometrically, we notice that if the angle between the two vectors of the cross product is zero, then $a=b=c=0$, but this is not permitted in the specification of a plane. This requirement means that the vectors in the cross product must be linearly independent (so the three points must not lie on a straight line in three-dimensional space) if these three points are to be used to define a plane. The specification of the plane is completed by setting $d=-[au_x^i+bu_y^i+cu_z^i]$, for $i=1$, 2, or 3.

A family of parallel planes can be described by a unit vector $\mu=[\mu_x\ \mu_y\ \mu_z]^t$ which is orthogonal to the planes in this family. The family of planes is given by $p=[\mu_x\ \mu_y\ \mu_z\ d]$ where d is arbitrary. A specific d produces a unique plane. Suppose p is required to pass through point $[x\ y\ z\ ]$ then $d=-\mu_xx-\mu_yy-\mu_zz$.

Location of a Plane with Respect to the Origin. The line from the origin to the point on the plane at a minimum distance from the origin must be normal to the plane, and so has a direction the same as the vector $[a\ b\ c]^t$ partially defining the plane; the line from the origin is

$$\begin{bmatrix}0\\0\\0\\1\end{bmatrix}+\alpha\begin{bmatrix}a\\b\\c\\0\end{bmatrix}$$ which intersects plane at $[a\ b\ c\ d]$ at $\alpha a^2+\alpha b^2+\alpha c^2+d=0$, or $\alpha=-d$.

The distance of point $\begin{bmatrix}-da\\-db\\-dc\\1\end{bmatrix}$ from the origin is $\sqrt{d^2a^2+d^2b^2+d^2c^2}=d$.

In a similar manner, the minimum distance from any point to the plane can be established.

Intersection of a Line and a Plane and the Minimum Distance from a Point to a Plane. The point of intersection of the line $u+\alpha(v-u)$ with the plane p is given by

$$p\{u+\alpha(v-u)\}=0, \quad \text{so} \quad \alpha=-\frac{pu}{p(v-u)} \tag{5}$$

Suppose we wish to find the minimum distance of point $\mathbf{u}=[x\ y\ z\ 1]^t$ from the plane $\mathbf{p}=[a\ b\ c\ d]$. Vector $[a\ b\ c]^t$ and point u define the line $u+\alpha[a\ b\ c\ 0]^t$ and this line must intersect the plane at point v such that the distance between points **u** and v is a minimum. The line intersects the plane at $\mathbf{pu}+\alpha p[a\ b\ c\ 0]^t=0$,

$$\text{so } \alpha=-pu \text{ and } v=u-pu\begin{bmatrix} a \\ b \\ c \\ 0 \end{bmatrix}=\begin{bmatrix} x - (ax+by+cz+d)a \\ y - (ax+by+cz+d)b \\ z - (ax+by+cz+d)c \\ 1 \end{bmatrix} \tag{6}$$

Position of a Plane with Respect to a Point and the Origin. The line joining a point $\mathbf{u}=[x\ y\ z\ 1]^t$ to the origin is $(1-\alpha)u+\ \alpha[0\ 0\ 0\ 1]^t$. This line intersects plane $\mathbf{p}=[a\ b\ c\ d]$ at $(1-\alpha)\mathbf{pu}+\alpha d=0$, the location of the point of intersection of the plane on the line is given by

$$\alpha=\frac{pu}{pu-d} \tag{7}$$

$$\text{If } \alpha \begin{cases} < 0 & \text{the plane is outside } \mathbf{u} \text{ with respect to the origin,} \\ = 0 & \text{the plane passes through } \mathbf{u}\ (\mathbf{pu}=0), \\ = 1 & \text{the point is at the origin } (d=0), \\ > 1 & \text{the point is on the other side of the origin with respect to } \mathbf{p}. \end{cases}$$

Intersection of Planes. The line of intersection of two planes will intersect another plane provided the angle between the vector specifying the direction of the line and the vector partially specifying the plane are not orthogonal. Except for the degenerate case when $\mathbf{p}_1$ or $\mathbf{p}_2$ is parallel to the x-y plane, the line of intersection of the two planes $\mathbf{p}_1=[a_1\ b_1\ c_1\ d_1]$ and $\mathbf{p}_2=[a_2\ b_2\ c_2\ d_2]$ must cross the x-y plane at $z=0$. At the x-y plane,

$$[a_i\ b_i\ c_i\ d_i]\begin{bmatrix} x_1 \\ y_1 \\ 0 \\ 1 \end{bmatrix}=0,\ i=1 \text{ and } 2, \text{ so}$$

$$\begin{bmatrix} a_1 & b_1 \\ a_2 & b_2 \end{bmatrix}\begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = -\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \text{ or } \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} = \frac{-1}{a_1b_2-b_1a_2}\begin{bmatrix} b_2 & -b_1 \\ -a_2 & a_1 \end{bmatrix}\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \tag{8}$$

If the determinant $(a_1b_2-b_1a_2)$ is zero, x_1 and y_1 cannot be found since the line of intersection is parallel to the x-y plane. Similarly, the line must cross (except for the degenerate case) the x-y plane at point $[x_2\ 0\ z_2\ 1]^t$ and the y-z plane at point $(0\ y_3\ z_3\ 1]^t$, where

$$\begin{bmatrix} x_2 \\ z_2 \end{bmatrix} = \frac{-1}{a_1c_2-c_1a_2}\begin{bmatrix} c_2 & -c_1 \\ -a_2 & a_1 \end{bmatrix}\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \text{ and } \begin{bmatrix} y_3 \\ z_3 \end{bmatrix} = \frac{-1}{b_1c_2-c_1b_2}\begin{bmatrix} c_2 & -c_1 \\ -b_2 & b_1 \end{bmatrix}\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} \tag{9}$$

Thus, regardless of any degeneracy, we have determined the line of intersection.

NONSINGULAR TRANSFORMATIONS

Suppose point u is transformed to point v by operation A, then $v=Au$, where A is a nonsingular, 4 x 4, transformation matrix. A can transform (3-7) **u** to v by adding a vector (translation), rotating **u** with respect to the origin, scaling the point **u** with respect to its distance from the origin, inverting or imaging (as with a camera lens). Some movements are inconvenient to describe in terms of a single matrix (the homogeneous transformation); for example, the transformation involving the addition of a rotated vector to a point is better specified as the addition of two quantities. We will use the form that is most convenient in the application.

Translation of Points and Planes by a Vector. The translation of point $\mathbf{u} = [x\ y\ z\ 1]^t$ by vector $[\alpha\ \beta\ \gamma]^t$ is

$$\begin{bmatrix} x+\alpha \\ y+\beta \\ z+\gamma \\ 1 \end{bmatrix}=Tu=\begin{bmatrix} 1 & 0 & 0 & \alpha \\ 0 & 1 & 0 & \beta \\ 0 & 0 & 1 & \gamma \\ 0 & 0 & 0 & 1 \end{bmatrix}u \tag{10}$$

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$$\text{and} \qquad T^{-1} = \begin{bmatrix} 1 & 0 & 0 & -\alpha \\ 0 & 1 & 0 & -\beta \\ 0 & 0 & 1 & -\gamma \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

To translate a plane **p** we use $\mathbf{q}=\mathbf{p}T^{-1}$, then $\mathbf{q}\mathbf{v}=\mathbf{p}T^{-1}T\mathbf{u} = \mathbf{p}\mathbf{u}$, so point **v** is on plane **q** if point **u** is on plane **p**.

$$q=pT^{-1}=[a\ b\ c\ d] \begin{bmatrix} 1 & 0 & 0 & -\alpha \\ 0 & 1 & 0 & -\beta \\ 0 & 0 & 1 & -\gamma \\ 0 & 0 & 0 & 1 \end{bmatrix} = [a\ b\ c\ d'] \text{ where } d'=d-a\alpha-b\beta-c\gamma.$$

Rotation by Angle θ in Plane p. Given vector $\nu=[\nu_x\ \nu_y\ \nu_z]^t$ in plane $p=[a\ b\ c\ d]$ that is to be rotated by angle θ about point v on plane p to become vector η as shown in Figure 1. Suppose we construct a normal to vector ν from the end of η, then from Figure 1 we see $|\alpha|=|\eta|\cos\theta$ and $|\eta|\sin\theta$. Therefore

$$\alpha=\nu\cos\theta \text{ and } \beta=k\begin{bmatrix} a \\ b \\ c \end{bmatrix} x\alpha \text{ where k is a scalar and vector } \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

is directed into the paper in Figure 1.

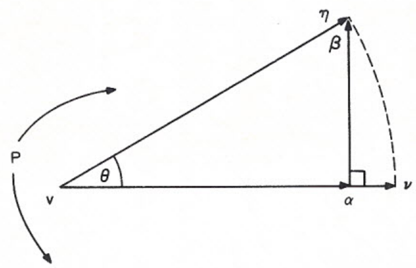

Figure 1. The rotation of vector ν about point v in plane p is illustrated.

The order of the cross product ensures that a clockwise rotation is positive. Vector α and unit vector $[a\ b\ c]^t$ are orthogonal, so $|\beta|=|k||\alpha|$, yielding $|k|=|\tan\theta|$.

$$\text{Thus } \eta=\alpha+\beta=\alpha+\tan\theta\begin{bmatrix} a \\ b \\ c \end{bmatrix} x\alpha=\nu\cos\theta+\sin\theta\begin{bmatrix} 0 & -c & b \\ c & 0 & -a \\ -b & a & 0 \end{bmatrix}\nu = \begin{bmatrix} \cos\theta & -c\sin\theta & b\sin\theta \\ c\sin\theta & \cos\theta & -a\sin\theta \\ -b\sin\theta & a\sin\theta & \cos\theta \end{bmatrix}\nu \tag{12}$$

Rotation of a Point about a Line. Given an axis or line $\mathbf{u}+\alpha(\mathbf{v}-\mathbf{u})$ and point w, if the direction of the line is used to partially define a plane p which contains w, then $p=[v_x-u_x\ \ v_y-u_y\ \ v_z-u_z\ \ d]$. Rotation of w by angle θ about the axial point with α defined by equation (2) will produce a new point $u+\alpha(v-u)+\eta$ where with the aid of equation (12) vector η is

$$\begin{bmatrix} \eta_x \\ \eta_y \\ \eta_z \end{bmatrix} = \begin{bmatrix} \cos\theta & -(v_z-u_z)\sin\theta & (v_y-u_y)\sin\theta \\ (v_z-u_z)\sin\theta & \cos\theta & -(v_x-u_x)\sin\theta \\ -(v_y-u_y)\sin\theta & (v_x-u_x)\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} w_x-u_x-\alpha(v_x-u_x) \\ w_y-u_y-\alpha(v_y-u_y) \\ w_z-u_z-\alpha(v_z-u_z) \end{bmatrix} \tag{13}$$

$$\text{The x, y and z-axes are defined by } \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix} + \alpha \begin{bmatrix} -1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix} + \alpha \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \text{ and } \begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix} + \alpha \begin{bmatrix} 0 \\ 0 \\ -1 \\ 0 \end{bmatrix}$$

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respectively, so a point on the x, y or z axis closest to a point $w = \begin{bmatrix} w_x \\ w_y \\ w_z \\ 1 \end{bmatrix}$

is at $\alpha=1-w_x$, $\alpha=1-w_y$, and $\alpha=1-w_z$ respectively. Rotation of w by angle θ about the x-axis produces point

$$\begin{bmatrix} \cos\theta & 0 & 0 & 0 \\ 0 & \cos\theta & \sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ w_y \\ w_z \\ 0 \end{bmatrix} + \begin{bmatrix} w_x \\ 0 \\ 0 \\ 1 \end{bmatrix} \equiv \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & \sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} w_x \\ w_y \\ w_z \\ 1 \end{bmatrix} = R_x \tag{14}$$

which is the result familiar to many (7). It should be pointed out that rotations about the major axes although extensively used (5,7,8) are not found to be so efficient and simple as rotation in planes (10) when applied to robotic movement (11).

Scaling. Scaling by scalar factor m changes **u** into $v=mu=um$. The transformation can be written in homogeneous form as $v=Gu$ where

$$G = \begin{bmatrix} m & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{15}$$

$$\text{and} \quad G^{-1} = \begin{bmatrix} 1/m & 0 & 0 & 0 \\ 0 & 1/m & 0 & 0 \\ 0 & 0 & 1/m & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{16}$$

Imaging. The imaging of a point is what happens when light passes through a thin convex lens as shown in Figure 2. Light from point u is imaged to point v, and center point w of the lens is in line with these two points. The plane of the lens is **p**. If D_1 is the distance between points **u** and **w** and D_2 is the distance between point **w** and v, then

$$\frac{1}{D_2} = \frac{1}{f} - \frac{1}{D_1} \quad \text{and so } v=w-\frac{D_2}{D_1}(u-w), \tag{17}$$

where $D_1^2=(u_x-w_x)^2 + (u_y-w_y)^2 + (u_z-w_z)^2$,

and $D_2^2=(v_x-w_x)^2 + (v_y-w_y)^2 + (v_z-w_z)^2$,

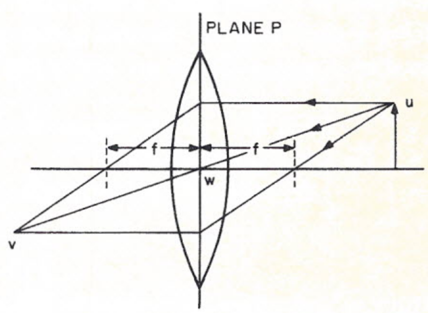

Figure 2. When light passes through a thin convex lens, light from point u is imaged to point v, and center point w of the lens is in line with u and v. The plane of the lens is p.

and where f is the focal length of the lens (the point to which all axial parallel rays of light will focus). Notice that $D_1 > f$ and $D_2 > f$.

It would be desirable to express point **v** in terms of point **u** as in $v=Mu$, where M is some homogeneous matrix, but this is not possible (except for some simple cases when the camera axis is one of the major axes) due to the implicit nature of equation (17).

An object can be defined in part as a collection of points in three-dimensional space. The transform will produce an image in three-dimensional space. The implication is that a clear image will be formed only at a film plane behind the focal point for a flat object parallel to the film plane on the opposite side of the lens. This is in contrast to the infinite depth of field that occurs in a pinhole camera. Provided that the object is small compared with its distance from the lens, the depth of field will not be a factor and the image can be captured in two dimensions without fuzziness. However, information is lost in the process because a three-dimensional object is imaged on a flat plane—this will be made evident when the pinhole camera is discussed. The non-singular transformation given in equation (17) does not lose information.

SEQUENCES OF TRANSFORMATIONS

Consider a sequence of translations and rotations on vector **u** such as $v=L_{xf}G_mT_\alpha R_{y\theta}u$ (18)

This represents the following operations on **u**

1. Rotation of point **u** by θ within a particular plane.
2. Translation of point $R_{y\theta}$ **u** by vector α.
3. Scaling of point T_α $R_{y\theta}$ **u** by scalar m with respect to the origin.
4. Imaging of point G_m T_α $R_{y\theta}$ **u** along the x axis with a lens of focal length f.

However, nonsingular matrices of the form R_y, T, G, and L_x perform linear operations, and so

$$u = R_{y\theta}^{-1}\ T_\alpha^{-1}\ G_m^{-1}\ L_{xf}^{-1}\ v. \tag{19}$$

Thus, L_{xf}^{-1} images point v with a lens of focal length f, G_m^{-1} scales point L_{xf}^{-1} v by 1/m, T_α^{-1} translates point $G_m^{-1}L_{xf}^{-1}v$ by $-\alpha$ with respect to the origin, and $R_{y\theta}^{-1}$ rotates point $T_\alpha^{-1}G_m^{-1}L_{xf}^{-1}$ by angle $-\theta$ within the plane.

Matrices L, G, and T commute, meaning that these operations can be performed in any order without changing the final result. However, R matrices do not in general commute. The problems with the above approach are:

A) Imaging matrices of the type L_{xf} require the axis of the lens to be a major axis, whereas a more arbitrary axis is usually required.

B) To determine the Euler angles to find matrices of the form $R_{y\theta}$ is often inconvenient, particularly when considering the movement of a multi-axis revolute or cylindrical joint robot. Researchers are required to resort to complicated pseudo-axes at intermediate joints, a mechanism that is unnecessary using the methods advocated here.

Notice that we cannot use rotations in a plane with homogeneous matrices in sequences such as given in equations (18) or (19) since we must be assured that the point post-multiplying the rotation matrix and the vector being rotated lie in the plane of rotation. This may be considered a major disadvantage over the Euler angle rotations about the major axes. However, it is found that determining planes of rotation is advantageous and solid angle rotations in planes is more efficient computationally than the Euler angle approach (10). Homogeneous equations can be used throughout when considering rotation with Euler angles, and these have the clean look of simplicity not verified by computational efficiency.

PERSPECTIVE PROJECTION AND CAMERAS

A perspective view is easy to obtain with respect to any plane p and focal point w as shown in Figure 3. A perspective projection is found by projecting from a point **u** on the object to focal point **w** and determining the point of intersection **v** of this line with plane **p**. The line between **u** and **w** is given by $u+\alpha(w-u)$, and the intersection of this line with plane **p**, as given by equation (5), is the point

$$v = u - \frac{pu}{p\,(w-u)}(w-u) = u - \beta(w-u) = (1+\beta)u - \beta w \tag{20}$$

where scalar β is a function of object point **u**. Thus, we cannot write v as a function of **u** in explicit homogeneous matrix form. For some simple cases we can write the perspective projection in homogeneous matrix form where the matrix is singular, but find this too limiting.

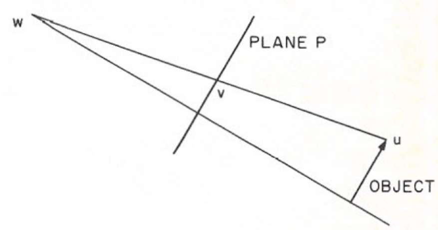

Figure 3. A perspective projection of an object is found by projecting from a point u on the object to focal point w and determining the point of intersection v of this line with plane p.

A pinhole camera produces an inverted perspective projection with the same equation (20). Notice, however, that p and v have a different orientation in this case. Such a camera is shown in Figure 4. The camera is a box that is light-tight except for a single pinhole. A point on the film plane at the back of the camera will receive light from any point along the projection line so the depth of view is infinite. All points in front of the pinhole and along a line passing through it strike the film plane at a unique point. An ordinary lens camera will produce the same image as the pinhole camera, provided the lens aperture is very small. For most robotic work we assume that the image is in focus so equation (20) applies.

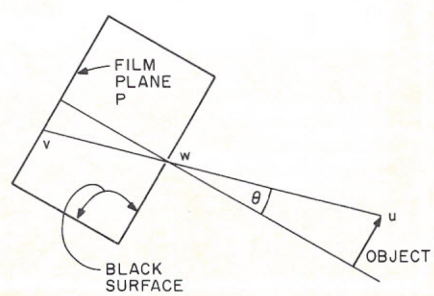

Figure 4. A point on the film plane at the back of a pinhole camera will receive light from any point along the projection line, so the field of depth is infinite. All points in front of the pinhole and along a line passing through it strike the film plane at a unique point.

CONCLUSION

The homogeneous representation has been shown to provide the appropriate basis for specification of the robotic workplace. On the other hand, the homogeneous transformation has been shown to be less efficacious in defining rotation or imaging. Most of the relationships needed to determine the geometry of a practical robotic system have been presented, enabling robots and objects to be modeled or imaged and so remotely controlled. For example, two independent camera images of a robot and its workpieces can be used to find the joint status of the robot and the true location of the workpieces in three-dimensional space.

The way the geometry of the robotic workplace has been developed reveals a methodology that has been applied directly to robot kinematics (10,11). It is hoped that other researchers will find the techniques of use.

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A Real-Time Three-Dimensional Vision System for Robotic Guidance

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Mountain View, CA 94043

As industry has gained experience using robots, it has been found that frequently robots cannot be used effectively without a machine vision system for guidance. Furthermore, in a growing number of instances a three-dimensional vision system is required for robotic guidance. Although many firms are marketing machine vision systems, only a small number of these systems have three-dimensional capability. Until now, a three-dimensional vision system small enough to fit on a robot arm yet provide truly real-time updates to the robot has not been available.

The VLS-200 Solid State 3-D Vision System from Applied Scanning Technology is such a system (Photo 1). It has a source sensor module (containing both a laser and a camera) which weighs less than four pounds, and it provides 240 sets of XYZ coordinates in 17 ms.

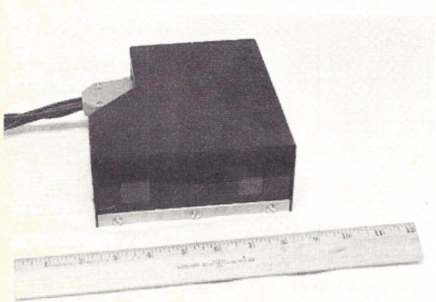

Photo 1. The Source-Sensor Module of the VLS-200 solid-state three-dimensional vision system contains both a laser and a camera.

TYPES OF THREE-DIMENSIONAL VISION

A variety of technical approaches for achieving 3-D vision have been investigated. One approach is optical radar or ranging. It involves sending a beam of laser light to the object and measuring the time it takes to return. By doing this a large number of times, with each beam being directed at a slightly different part of the object, a three-dimensional map of the object's surface can be constructed. However, this approach requires measurement of the beam's transit time in the pico second range, which is difficult. Also, optical ranging by its nature requires some time to construct one image since each image consists of a significant number of points. If, for example, a 400 by 400 element image is desired, and each element takes 100 ms to be developed, one entire image would take 16 sec. to construct. This approach is therefore not ideal for real-time updates, except for where only a few range data points are required.

Another approach involves triangulation ranging of a point source of laser light. Here, a very small point of laser light is directed at the object and a camera mounted at a nominal 45 degree angle to the source detects the reflected light. Because the camera is at an angle to the laser, two-dimensional coordinates can be obtained. A large number of these points can be assembled to provide a three-dimensional map of an object's surface. This approach is being used in a number of applications requiring extreme accuracy. Its main drawback is the relatively long time required to put together an image from the thousands of observed points. The time needed to construct one image is similar to that of optical radar as indicated above.

A third approach, which is an extended form of laser triangulation ranging and the one used by the VLS-200, is called structured light. It calls for directing a thin line of laser light (rather than a point) at the object to be mapped (Figure 1). The

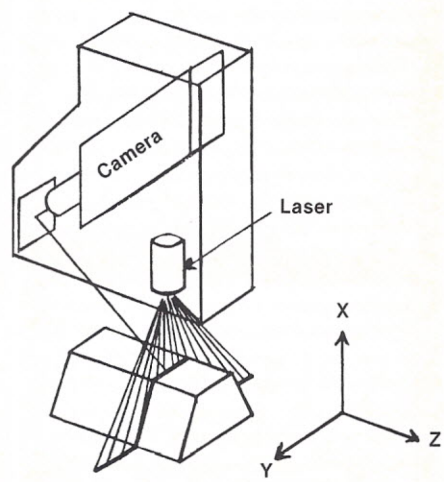

Figure 1. A thin line of laser light is directed at the object to be mapped.

1986 Rochester Forth Conference

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The sixth Rochester Forth Conference will be held at the University of Rochester, and sponsored by the Institute for Applied Forth Research, Inc. The focus will be on Real-Time Artificial Intelligence, Systems and Applications.

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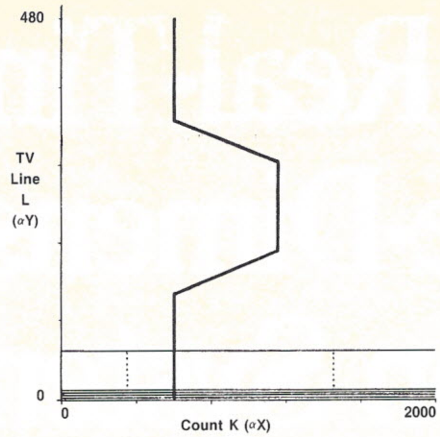

Figure 2. The system's camera, viewing the object at a 45 degree angle from the laser line, produces a two-dimensional contour of that object.

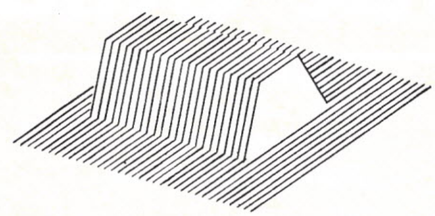

Figure 3. A series of rapidly produced, closely spaced two-dimensional contours produces a three-dimensional image.

system's camera again views the object at a 45 degree angle from the laser line, and detects a two-dimensional contour of the object (Figure 2). The resulting three-dimensional description is made up of a series of rapidly produced, closely spaced two-dimensional contours (Figure 3). Because of a line of light consisting of 240 points, rather than one point of light, is employed, the system can construct an image on the order of 200 times faster.

Development of this technology was first disclosed in 1975 by Weyerhaeuser Company with Leon Chasson, now President of Applied Scanning Technology, designated as inventor. U.S. Patent 4,188,544 on structured light technology and the necessary calibration technique and high-speed digital preprocessor design, was granted in 1980 to Weyerhaeuser Company. At this time, Applied Scanning Technology is the only licensee for this technology.

AST systems has been successfully running in harsh manufacturing environments for five years (Photo 2). AST believes that structured light technology's combination of reliability, accuracy, and speed will make it a useful and effective form of 3-D vision for the foreseeable future.

THREE-DIMENSIONAL VISION FOR ROBOTIC GUIDANCE

The recent availability of gallium arsenide laser diodes with significant power output and miniature solid state TV cameras has allowed development of a structured light vision system with the small size and high speed required for effective robotic guidance. This system is the VLS-200 Solid State 3-D Vision System. Its Source-Sensor Module, including the camera, laser, and proprietary electronics, is contained in a 6.1 by 6.7 by 2.5 in. package weighing approximately 3.5 lbs. The module is ideal for mounting on a robot arm. Its small size is useful also in applications other than robotic guidance. With the VLS-200, the vision system can be moved around a large object rather than moving the object around the vision system. Also, the Source-Sensor Module could be built into equipment for real-time monitoring to improve a customer's process control. With this size, a portable three-dimensional vision system is possible.

The high-speed digital preprocessor allows the VLS-200 not only to acquire 14,400 three-dimensional data points per second, but also to provide the same number of XYZ coordinates per second. This corresponds to outputting 240 coordinate sets every 17 ms. In addition, the VLS-200 can freeze object motion by using the pulsed laser as a strobe device. This allows accurate measurement of objects moving as rapidly as 40 in./s.

The system will calibrate itself whenever the user requests it to. It does so by observing reference surfaces placed in the field of view next to the object and automatically correcting for camera and lens nonlinearities, parallax, and other error sources. The entire calibration procedure takes less than two minutes.

The VLS-200 can be configured for accuracies of as small as 0.001 in. (0.025 mm). Configuration options are available allowing up to eight Source-Sensor Modules to be included with one system. This allows larger fields of view without compromising accuracy. Reliability is expected to surpass that of the field-proven previous generation of three-dimensional vision systems from AST. The solid-state laser replaces the helium-neon laser of previous systems, and the solid state camera replaces the Vidicon TV camera.

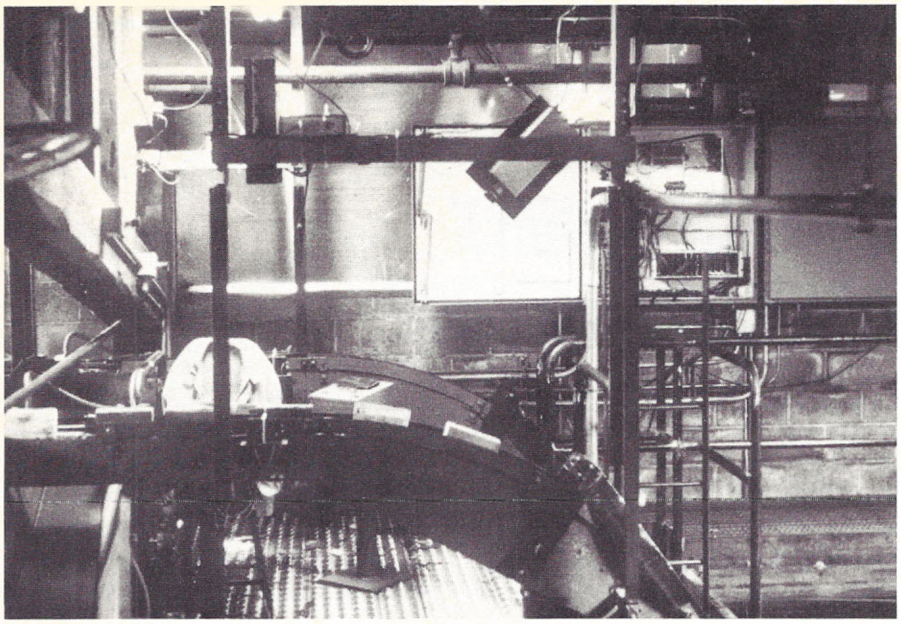

Photo 2. Two VLS-100 three-dimensional vision systems from Applied Scanning Technology have been reliably sorting wood blocks for pencil manufacturing for five years at Hudson I.C.S. in San Leandro, California.

SYSTEM CONFIGURATION

Complete VLS-200 systems for production applications consist of the following main elements:

1. One or more miniaturized Source Sensor Modules, each one including a solid state laser, a solid state camera, and pulsing electronics
2. A 42.5 MHz digital preprocessor and 68000-based computer system using the VME bus in either a NEMA enclosure or rackmount cabinet
3. A variety of software functions including calibration, diagnostics, RS-232 and RS-422 host computer interfaces, and control of one- or two-axis linear positioning stages
4. A menu-driven application software package integrating all system functions into one user interface that allows the user to select the spacing between two-dimensional contours, smooth data over time and space, and generate a data base of XYZ coordinate sets for analysis and output in either graphic, textual, or binary format

Also available is a configuration that allows the computer system to be used for development as well as production. This configuration includes a C language compiler, development utilities such as a debugger, and a 10 Mbyte hard disk. In addition, VLS-200 systems are available in board level or box level configurations. This allows robot manufacturers to integrate the vision system into the robot at a variety of levels.

SEAM TRACKING APPLICATION

The first VLS-200 has been shipped to a major American automobile manufacturer, which will use it for seam tracking. In this application, the lightweight Source-Sensor Module is mounted on the robot arm, which moves rapidly along a welded seam and applies sealant. Seam recognition software has been developed, allowing the seam to be tracked at 40 in./s. A known good seam is stored in the VLS-200 memory during teach mode. Then, in production, the system acquires the surface contour of the seam to be tracked, matches the production seam to the stored one, and sends the difference in coordinates between the two seams (offset) to the robot controller. All of this is done in under 125 ms.

Jim Simmons is Vice President of Marketing for Applied Scanning Technology.

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SURFACE-MOUNT TECHNOLOGY REPORT

Molex Incorporated manufactures interconnection components for the electronic and electrical OEM market. Its customers include Zenith, Chrysler, Xerox, IBM, Sony, Philips, and Delco Electronics. Many of these companies routinely use robots on their assembly lines, and many are turning to surface mounting for their printed circuit board components. Robotic assembly and surface-mountable devices were made for each other. Let us look at what one company is doing with the new technologies.

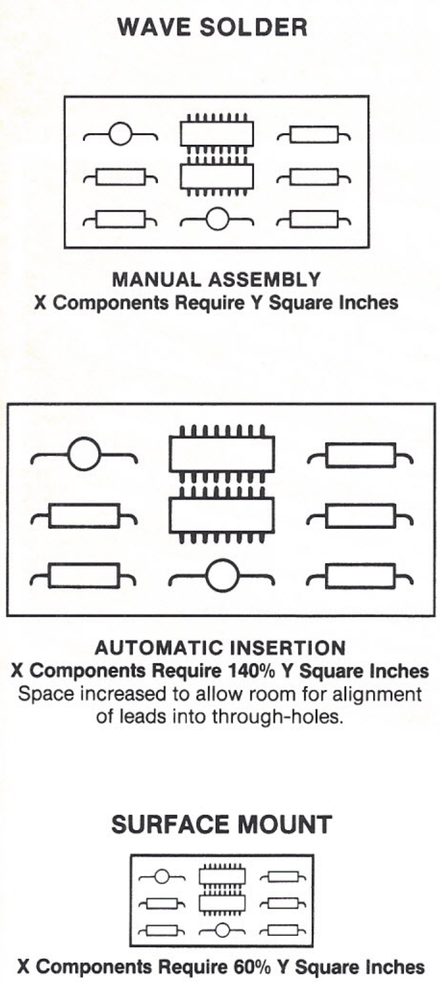

Figure 1. Surface-mount components are typically smaller and can be more closely spaced than through-hole components.

Surface-mount technology (SMT) is an old process that has returned after 20 years to become the new darling of printed circuit board packaging. SMT involves the attachment of components to one or both sides of a PCB without the use of through holes for contact leads. Developed for dense electronic packaging where space limitations dictate, components are smaller, and board preparation costs are lower, SMT offers a variety of advantages over conventional board design (Figure 1). Space savings translate to shorter interconnection paths and correspondingly better high-frequency operation. Productivity is improved as well with the use of automated equipment to populate the boards.

Surface-mountable components, whether leaded or leadless, are attached directly to the surface of a substrate with or without adhesive and are subsequently reflow soldered via wave, infrared reflow (favored in Japan), vapor phase reflow, or other methods. Although there is not yet an industry standard, the most widely used attachment process in this country is the vapor phase solder method, in which a paste of solder (typically 63 percent tin/37 percent lead or 60 percent tin/40 percent lead) and flux is stenciled or screened to PCB pads. The components are placed on the pasted areas and held until the assembly is passed through a chamber where it is engulfed in layers of vapor created by boiling fluorinert liquid at 215° C. At about 188° C the solder paste liquifies, forming a fillet that connects the PCB pads to the components after solidification. Because the vapor heats evenly, this process greatly minimizes the board rework necessitated by solder-bridging and icicling and decreases the potential for component damage (Figures 2 and 3).

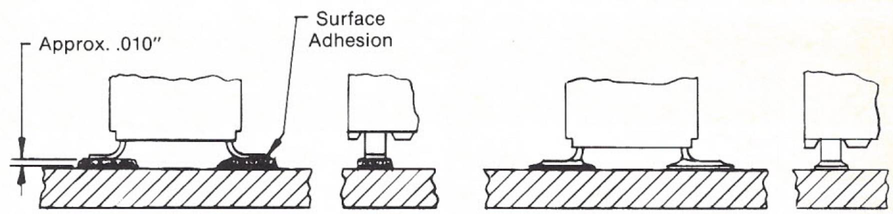

Figure 2. The vapor phase solder method of curing SMT boards heats evenly, minimizing board rework necessitated by solder-bridging and icicling.

Molex developed a surface-mount program while addressing new connector designs that are both SMT-specific and

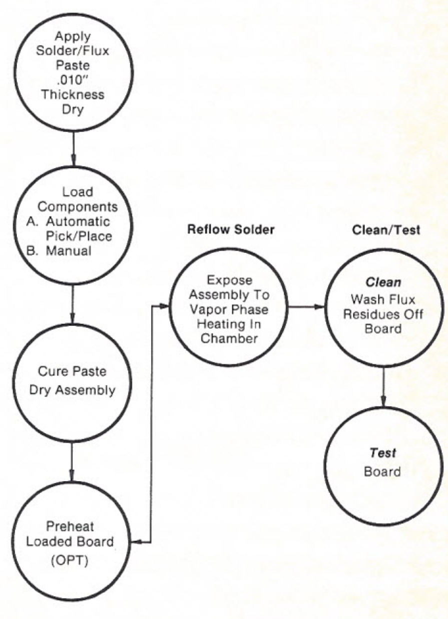

Figure 3. The stages of the vapor phase reflow method are outlined.

robotically placeable (Photo 1). A new insulator material—PET polyester—was chosen based on a cost/performance tradeoff and because of its stability at high reflow temperatures. Gull wing contact leads were designed to conform to the PCB pads.

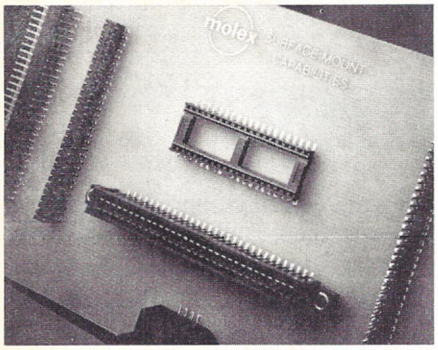

Photo 1. Molex manufactures a variety of surface-mountable connectors.

Ideally, the PCB should have no holes so that dense component packaging can be achieved on both sides of the board. Molex has, however, determined that connectors might need retention/alignment pegs to hold them during the vapor phase reflow process; there are thus holes, but a minimal number, in the boards. The components that have adapted most readily to surface-mount techniques are small, lightweight chip carriers, resistors, small outline transistors, small outline ICs, plastic chip carriers, and leadless chip carriers, none of which Molex makes. So, our challenge is to convert larger, multi-contact, higher profile PCB components to conform with SMT specifications.

Molex R&D engineers have been experimenting with a Universal brand point-to-point servo robot for the last 18 months. Besides placing a variety of Molex interconnection parts onto PC boards, the robot has been the focus of connector packaging and delivery systems. Four packaging systems were created to interface with robotic pickup stations. Delivery systems (end tracks) complement the packaging and ensure the part gets picked up from the package and properly placed on the board.

Molex's systems approach to SMT and automated printed circuit board assembly is in keeping with the prediction of Irv Triner, Molex project manager, that by 1990 SMT will be the dominant method of printed circuit board manufacture.

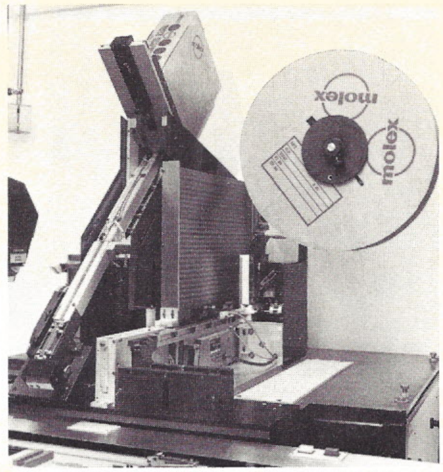

Photo 2. A Molex packaging system delivers to a robot's end effector connector devices to be placed on a PC board.

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ADHESIVE BONDING FOR METALLIC PARTS ASSEMBLY

Increasing profits while maintaining a competitive edge is the constant goal of management in mass manufacturing. In the past, such aims often resulted in a creeping erosion of product quality because cost considerations usually had top priority. Today, with increasing pressure from overseas competition, management expects the manufacturing engineer not only to come up with continual improvement in the cost picture, but also to raise product quality at the same time.

One of the newer manufacturing techniques that consistently offers large cost reductions while improving quality is adhesive bonding for permanent assembly of metal parts. This approach cures many of the headaches which form part of the production man's daily fare.

It has long been known that two metal parts, or parts made of dissimilar materials, could be reliably bonded together with suitable adhesives. The aircraft and automobile industries have used such materials increasingly since World War II. Today's rapid expansion of adhesive bonding has had to wait for development of a way to apply the adhesive quickly and accurately, and exactly where it is needed.

The right way to do the job has proven to be with computer-controlled robots. These machines can lay down an adhesive bead on a part at speeds as fast as 2000 in./min., within a few thousandths of the chosen path on the part, in a precisely determined amount, and never spill a drop. With such machine ability and dexterity to command, it is not surprising that auto companies in particular have quickly begun to exploit the potential of adhesive assembly techniques in high production. Today, the method is becoming standard practice for many auto parts, such as door assemblies (Figure 1, Photo 1).

Cost savings lie in several areas. For one, adhesive bonding is cheaper in many cases than spot welding because tooling-up costs are considerably lower, electrode maintenance is eliminated, and extraordinary safety precautions need not be taken in the workplace. While a welding machine is likely to be single-purpose equipment, the robot adapts easily to a part change—or even to a new job—without alterations except to the set of electronic instructions prepared for it.

Although the path the head travels while laying down an adhesive bead can be very complex, machine programming is relatively simple. Accuratio Systems Inc. (A.S.I.), which has built more adhesive application robots than any other company, needs only a few days to teach an apt person without previous programming experience how to program a robot to lay adhesive.

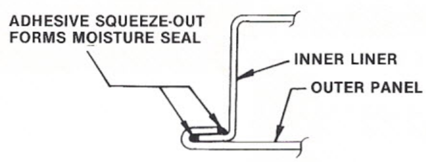

Figure 1. In a typical car door construction the flange is bent over to make a triple thickness of metal at the door edge. The adhesive not only strengthens the joint and reduces squeaks and rattles, but also forms a seal to keep moisture out.

Photo 1. The edges of the rear window of a station wagon are first given a coat of adhesive and then flanged over to form a triple thickness of metal. Squeeze-out from the adhesive forms a seal against moisture.

In auto plants, a distinct quality improvement is gained in the assembly of such highly visible parts as doors, hoods, and deck lids. Here, where stiffening liners are assembled into the shells, mechanical fastening is not feasible and spot welds frequently announce their presence with unsightly marks in finish paint. (These, of course, demand that the part be refinished.) Adhesive bonding not only eliminates such blemishes, but also ensures that squeaks and rattles will not develop when the car takes to the road. With stresses distributed over a wide area rather than at a series of small spots, the assembly is stronger. Further, while body corrosion often begins at or near weld spots, the adhesive can also function as an effective sealant against moisture. There are product design benefits in adhesive bonding as well. For example, openings do not have to be provided in strategic locations to admit welding electrodes, so the part can be designed for maximum rigidity and minimum die cost.

Adhesive formulas are available now to suit almost any purpose. They come with characteristics for maximum bonding strength appropriate to a variety of materials, and in varying viscosities and degrees of tackiness. In one application, for instance, the adhesive is laid in place on a glass panel in an "O" cross section and has barely enough tack to hold it in place on the glass during assembly into the vehicle (Figure 2). This forms a flexible gasket that can be readily removed in case

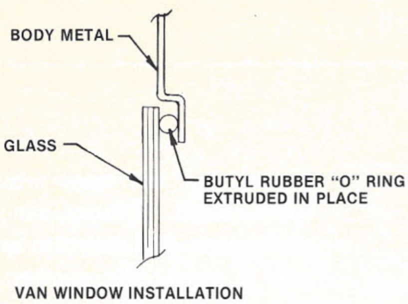

Figure 2. In a van window installation a butyl rubber material is extruded to a specific cross section to form an "O" ring. The material's stiffness requires a pressure at the nozzle of 6000 psi.

it becomes necessary to replace the glass. More than 6000 psi is needed at the nozzle to extrude the material onto the glass. In other applications, the adhesive is laid on at a nearly liquid consistency so that gravity alone compresses the bead to bring the parts together. In some applications only adhesive strength is required of the bond. In others, it must perform an effective sealing or gasketing function as well.

In applications where considerable bonding strength is a requirement, epoxy adhesives are commonly used. While these can be two-part formulations, mixed at the same nozzle and cured through an exothermic reaction, they are generally applied to one of the parts at room temperature and cured after the parts have been brought together, painted, and the part temperature is raised in the paint drying oven. Mechanical means are required in such operations to hold the parts in alignment until they reach the oven.

In almost all adhesive bonding and sealing jobs there is a requirement for precise control of the amount of adhesive applied and of the bead's location on the part. Four factors are involved in control of adhesive quantity: consistency or viscosity of the material, pressure at the nozzle, size of the nozzle, and speed of the machine. Once specifications are set up, it is a relatively simple matter to control the amount of bead. In fact, the amount of adhesive laid on the part can be varied during a cycle by deliberately varying machine speed at certain points to produce a heavier or lighter bead where desired.

Bead placement, though, is entirely a function of machine efficiency. A.S.I.'s control is via computer actuation of servo motors that can position armatures to within a few degrees of rotation. Machine rigidity, too, is an important factor in the ability to place the bead routinely within 0.010 in. of its planned position, or closer if production requirements so dictate.

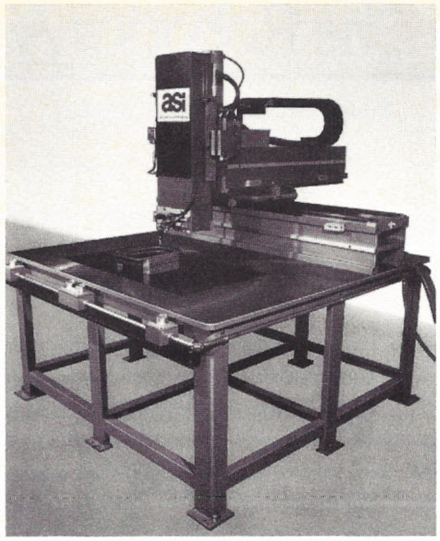

Photo 2. A cantilevered robot is compact, versatile, and suitable for applying adhesives to small and medium sized workpieces.

A.S.I. produces a number of standard sizes and configurations of robots as well as specially designed and built machines. Compact cantilever-type machines (Photo 2) prove handy in many applications while large gantry types straddle the production line in others. Five-axis capability is commonly specified. The five-axis machines can establish and maintain a specific nozzle position relative to the part no matter how complex its configuration or the direction of machine travel. This keeps the bead perfectly uniform.

Records based on queries to customers indicate that in addition to delivering improved product quality, most A.S.I. adhesive bonding and sealing installations pay for themselves in less than a year.

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Clawson, MI 48017

Edited by Stephanie vL Henkel

AUTOFACT '85

Autofact '85, "Manufacturing Integration Comes of Age," can be summarized in 21 letters: CAD, CAM, CAE, CIM, LAN, TOP—and, above all—MAP. In a one-quarter acre display shared by 22 exhibitors, General Motors created a totally automated factory that produced the Towers of Hanoi brainteaser game. "Customers" entered their orders at remote stations and were assigned numbers, and from then on the robots were in charge. The setup also demonstrated the virtues of just in time inventory control, and we could imagine a large-scale version building automobiles to order.

General Motors Corp. unveiled MAP, Manufacturing Automation Protocol, in July, 1984, at the National Computer Conference and suddenly the vendors of computerized manufacturing equipment had to get serious about the interoperability to which they had long been giving lip service. Simply put, MAP's objective is to establish a single protocol that will enable computer, robotic, and communication systems made by different manufacturers to communicate with each other.

A company the size of GM can by sheer strength make industry standards happen, but judging from MAP's reception, far from being shoved down various corporate throats the standard was being eagerly embraced. Hewlett Packard, for example, had developed its own early version of MAP, FutureNet, based on the same seven levels GM established. HP has agreed to support MAP while continuing to support FutureNet. Everyone seemed in on the MAP act by the end of the conference; nearly every display in the hall sported a banner: "We Support MAP."

Autofact's primary focus was on computers and software. The CAD graphics were spectacular, but not many were robot-related. Software kinematics packages have yet to appear in appreciable numbers. There were, in fact, very few robots on display. McDonnell Douglas offered a tour of an automated factory that culminated in a robotic welding demonstration and the line to get in stretched hundreds of feet.

Altogether there were 220 exhibits in over 130 categories of computer-based engineering, manufacturing, and management technologies and equipment. The official attendance figure was set at 33,107, a sizeable jump from last year's 22,776. Twenty-five countries were represented, including the U.S. and Canada.

PEOPLE

►**Eric Mittelstadt**, president and CEO of GMF Robotics, has been elected president of the **Robotic Industries Association**. He succeeds in that office **Walter K. Weisel**, president and CEO of Prab Robots. Mittelstadt's one-year term will officially begin at the RIA's annual meeting in January, 1986.

► **Imaging Technology Incorporated** has announced two appointments: **Donald R. Young** as a member of the board of directors and **Gary Mayerick** as vice president, engineering. Young is an associate of Fidelity Venture Associates. Prior to attending Harvard he was a centerfielder for the Atlanta Braves. Mayerick was formerly with Imagitex and the Verbex division of Exxon Enterprises.

► **James McGrath** has been appointed robotic systems engineer at **Advanced Technology Systems**, where he will be responsible for integrated robotic systems. **Cheryl A. Comai** has been named manager of marketing and planning. Comai was formerly assistant director of the Robotics Research Center at the University of Rhode Island.

► **Perceptron, The Machine Vision Company** has named **Arthur R. Smith III** CEO of the first business unit. Smith, who joined Perceptron in 1984, was previously with Control Data and other high-tech firms. The company also named **Gregory H. Knudson** director of marketing services. Knudson also manages Perceptron's new international operations in Munich, West Germany.

► **Intelledex Incorporated** has named as VP-operations **William I. Robinson**, former president of European operations for Measurex and most recently president of Ahlstrom Automation Inc. Robinson will be responsible for the manufacture of the firm's turnkey automation systems and standard robot and vision products.

► **Unimation Incorporated** has appointed **Harold H. Bloch** vice president of marketing. Bloch, who has been with the firm since 1960, was most recently vice president of systems engineering.

► **Javelin Electronics** has announced two appointments: **J. David Bittner** is now director of corporate accounts and **Russell J. Mayworm** is national sales manager. Bittner will direct negotiations and corporate relations for large accounts. Mayworm was formerly vice president of North American Computer and division manager of Sanyo Electric's CCTV division.

► **Feedback Inc.** has appointed **Ian H.H. Smith** sales director. Smith has worked for UPI, Muirhead, Inc., and Plessey.

► **Selective Electronics, Inc.** (Selcom) has named **Ronald F. Miller** Midwest Optocator sales engineer and **Richard C. Hunt** applications engineer. Miller will be responsible for the Optocator measurement system and Hunt will cover Selspot and Optocator applications.

►**J. Ross O'Hanlon, Jr.** has been appointed regional manager, NC Software Products, for **Automation Intelligence**'s Northeast region. Prior to joining AI, O'Hanlon was with Cadlinc.

In The Robotics Age™

SCIENCE & TECHNOLOGY

An advanced x-ray scanner that allows factory inspectors to look into the inside of aircraft engine turbine blades is being used at the **General Electric** plant in Madisonville, Kentucky, and a next-generation module is nearing completion that will give the computer enough intelligence to recognize flaws and decide on its own whether to accept or reject a part.

The x-ray module is part of a highly automated blade inspection system designed to assist in the detection of internal casting flaws and manufacturing errors such as misdrilled cooling passages. The process is filmless, yielding clearer and more detailed images and eliminating such variables as film quality, processing chemicals, and operator experience. In this method, x-rays penetrating an object are read by a detector and interpreted by a computer to form an image.

The blades are carried into the inspection module on a conveyor. A robotic manipulator grasps each blade and automatically positions it in the x-ray beam according to the type of scan requested. After inspection, the robot replaces the part on the conveyor and it is returned to the operator. A blade is first viewed for 30 seconds in a digital fluoroscopy mode, which produces a flat plane image analogous to a conventional x-ray. If irregularities seems to be present, the part can be reinspected in the computed tomography mode, a two-minute operation that creates a cross-sectional image which permits a direct measurement of inner features.

A program to develop accessories that will enable high-power lasers to be used for materials processing is being proposed by **Battelle** Columbus Division. The project, to be supported by several companies, is aimed at developing optical accessories for lasers used by robots for cutting, welding, and surface modification. With an increase in the power and the size of laser-based materials handling machines have come a number of problems. The large amount of waste heat created by the high-power lasers contributes to beam-pointing instabilities. Also, the larger lasers have been unable to produce pulsated beams, power variations can alter the beam's alignment, and high laser powers can cause thermal deformation of optical devices.

Battelle's proposed study is expected to lead to the development of generic optical devices for types and powers of lasers, including those able to handle more than 5000 watts of continuous carbon dioxide laser power. Devices under consideration are: a variable speed, continuously variable-duty cycle chopper for production of pulsed power from a continuous beam; a beam-pointing control system for maintaining beam alignment along robots' rectilinear paths; a cone-parabola axicon for reflective coaxial focusing of various high-power beam types; and a kaleidoscope beam integrator for production of square- and rectangular-beam images of uniform power density.

CORPORATE NEWS

►**Allen-Bradley** has announced an agreement to acquire the Interactive Systems business unit of **3M Corporation.** The newly acquired unit is a supplier of LAN electronic communication products. It will become the Communications Division of A-B's Industrial Computer Group and will remain in Ann Arbor, Michigan. Allen-Bradley has also announced the formation of a business unit to market industrial automation products and systems to the federal government. Rockwell, A-B's parent company, is among the largest U.S. gvernment contractors.

► **Gould Inc.** has formed a single industrial automation sales organization, combining the sales groups of three divisions that serve the firm's customers for factory automation systems and products. The new organization consolidates the domestic sales forces of Gould's recently acquired International Cybernetics Division, Motion Control Division, Programmable Control Division, and the Troy, Michigan, sales office of the Computer Systems Division.

► **Machine Vision International Inc.** has received new orders for glass adhesive inspection systems to be installed at two car assembly plants for a major auto manufacturer. The systems are designed to verify that the correct glass is present, inspect black primer and urethane applications, and automatically record data to facilitate compliance with the federal Motor Vehicle Safety Standard requirements.

► **Cincinnati Milacron**'s Industrial Robot Division is installing a three-robot gantry in **Ford Motor Company**'s Chicago stamping plant. The robots are to weld aluminum hinge and latch brackets onto engine compartment hoods. The firm has also received a $6.5 million contract to build T³ 886 gantry robots for GM's Truck and Bus Group. The robots will be used for spot welding and will be equipped with MAP interface.

► The **National Aeronautics and Space Administration** has awarded a contract to **FTG Data Systems** for the development of a Tektronix 4025 emulation. Faced with a large body of existing software but no new 4025 terminals from Tektronix, NASA chose to go with terminal emulation software.

► **Spectragraphics Corporation** has announced that **Apollo Computer, Inc.** plans to make a $3 million initial equity investment in that company and to sign an $800,000 contract for product development as part of a strategic alliance between the two firms. Under the terms of the agreement, Spectragraphics will develop hard- and software that allows Apollo workstations to access IBM mainframes. Apollo will have the option to increase its investment, while retaining a minority interest in Spectragraphics and also to name a representative to that company's board of directors.

► **Adept Technology, Inc.** has signed an agreement with **Chad Industries** to market Chad's unique robotic components. The components enable Adept's AdeptOne™ to flexibly assemble standard and odd through-hole electronic devices into PCBs without changing end effectors or peripheral tooling. The agreement gives Adept exclusive rights to market the components, with the exception that Chad retains the right to design the components into turnkey systems it sells.

► **Industrial Networking Inc.**, a joint venture between Ungermann-Bass Inc. and GE, has entered into an agreement with **Fanuc Ltd.** of Japan to jointly develop local area network products that will provide full MAP capability for Fanuc products. According to IN president and CEO Joseph P. Schoendorf, the Fanuc program grew out of a development plan already under way with GMF Robotics, itself a joint venture between GM and Fanuc. The IN-Fanuc effort will be directed toward developing a board-level interface that supports the GMF/Fanuc backplane.

► The results of an evaluation conducted by *Forbes* have named **Flow Systems Inc.** one of the best small companies in the U.S. The magazine evaluated 4000 firms with sales between $1 million and $300 million and the top 200 were ranked according to their five-year average return on equity. To qualify for the list, the companies had to show consistence in earnings growth, balance sheet strength, an average five-year growth of 8 percent or better, and high return on equity.

► **Intelledex Incorporated** has appointed as its distributor for Singapore and other Asian countries **Chartered Electronic Industries PTD. Ltd.** The agreement marks the beginning of international distribution for Intelledex. CEI will also function as a systems house for the U.S. firm.

► **Robotic Computers, Inc.** has entered into an agreement with **Advanced Technology Applications Corporation** and **Advanced Technology Products, Inc.** whereby RCI will acquire all the outstanding stock of ATA and ATP. Upon completion of the acquisition, and without regard for the redemptive rights RCI included in the agreement, the current shareholders of ATA and ATP will own approximately 48 percent of the issued and outstanding stock of RCI.

Classified Advertising

New Products

Vision System for SMT Inspection and Control

Machine Vision International has introduced an image analysis product for use in automated inspection and control of surface-mount technology manufacturing. Electro-Vision 5000 inspects the SMT assemblies for proper distribution and proportion of solder paste, identification and registration of components, and quality of solder flow. The system is based on MVI's proprietary image processing technology and advanced image flow architecture.

The EV 5000 combines MVI's Image Flow Computer with the IBM PC. The PC provides interface to the operator, external devices, and host systems, and integrates the EV 5000 with the SMT manufacturing process at production line stations. System software, featuring MVI's proprietary BLIX libraries, manages all aspects of the machine vision process. The inspection and control system is ready to install on any SMT line and ready to run under any lighting conditions.

Features of the EV 5000 include CAD system interface for setup, menu driven commands for operator interface, and a range of communication interfaces to host systems and commercially available material handling systems. The system integrates controls for external equipment such as solder deposition and component placement systems, while producing computerized reports of defects to measure quality standards.

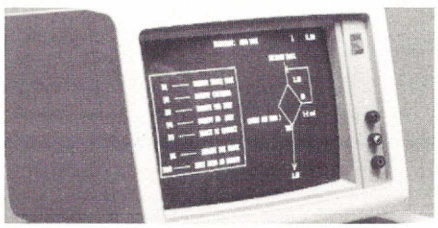
For more information, contact: Machine Vision International, Burlington Center, 325 East Eisenhower, Ann Arbor, MI 48104, telephone (313) 996-8033. Circle 60

Super-Miniature Solid State Camera

PULNiX has introduced a super-miniature solid state camera that is 4 in. long and weighs 5 oz. The TM-24 features a 244 by 244 pixel MOS imager with black and white RS-170 output through an F-type video connector. The camera comes in three versions: the TM-24S standard camera, the TM-24A with audio, and the TM-24T for computer interfacing. Each comes complete with 16 mm miniature C-mount lens and power connector plug for 12 VDC input.

The company offers a 1-year warranty on the camera and anticipates a 10-year lifetime. Environmental housings are available for hostile factory conditions.

For more information, contact: Mary Pomeroy, Sales Manager, Video Components, PULNiX America, Inc., 770-A Lucerne Dr., Sunnyvale, CA 94086, telephone (408) 733-1560. Circle 61

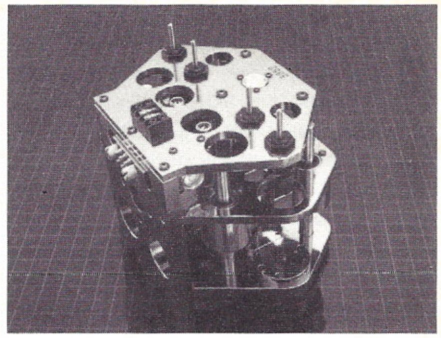


Control Software Development System

Universal Automation, Inc. has introduced the FloPro™ control software development system. Control applications can be developed, debugged, and controlled directly from an IBM PC or other system compatible computer. FloPro provides a method of taking an automation control application from concept to execution using decision flowcharts. No conversion to another computer language is required, enabling control software development time to be cut in half.

FloPro is a real-time multi-tasking system and is currently in use in a variety of control/monitoring applications (floppy disk certifier monitoring, rigid disk robotized certifier monitoring, warhead torquing, oscillator crystal sorting, and printed circuit board testing). A typical scan rate using FloPro is approximately 10 ms including I/O.

For more information, contact: Ruth A. Cook, Universal Automation, Inc., 23 Burnham Rd., Hudson, NH 03051, telephone (603) 880-6553. Circle 62



Robotic Sensor Probe

Automation Engineering has developed a special non-windowlocking, quick response, long over-travel sensor probe for deep cavity probing by robotic end effectors. The sensor is designed to probe for parts that remain unejected during robotic insert molding applications.

The robotic insert loading system, also designed by Automation Engineering, requires probing at an angle and deep inside four mold cavities simultaneously. To accomplish this, and to prevent windowlocking, a long hardened pin is placed inside a precision instrument grade ball bushing. The parts to be detected vary in thickness from 0.020–0.025 in., so immediate response with a long overtravel is required to prevent the robot from jamming if an object has not been ejected from the mold cavities. The pin and anti-windowlocking feature are housed inside a ½ in. 32-threaded mounting body for ease of mounting and precision position adjustment.

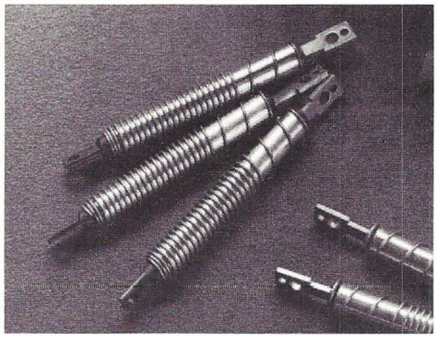
For more information, contact: Automation Engineering, PO Box 4311, Crestline, CA 92325, telephone (714) 338-3844. Circle 63

CAD For Robot Simulation

A CAD system available from Reis uses the Applicon System Bravo to simulate the workcell environment of Reis robots. Software developed by the firm includes kinematic and dimensional data. Robot movement can be computed and displayed from starting to end point, along with any selected intermediate position of the robot arm and tooling positions. Additionally, all machinery and equipment within the work envelope can be computed for possible collision problems.

For more information, contact: Reis Machines Incorporated, 1150 Davis Rd., Elgin, IL 60120, telephone (312) 741-9500. Circle 64

Shape-Memory Actuators

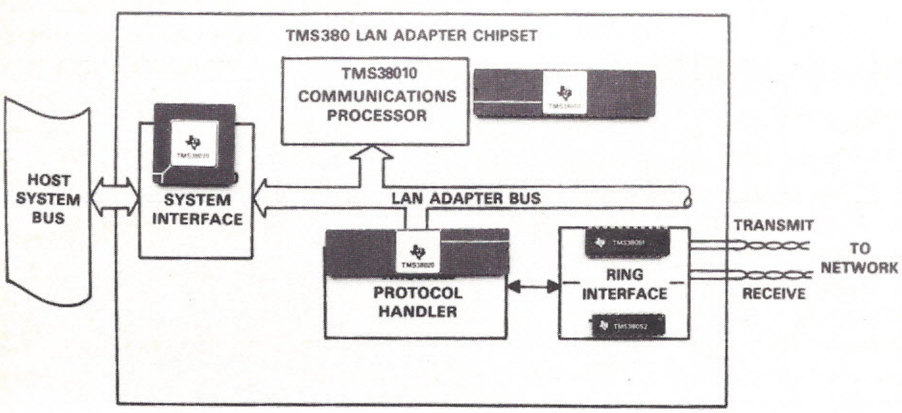


A general purpose linear actuator from Raychem uses shape-memory metal to perform electromechanical functions. Designed as an alternative to motors, solenoids, bimetallic strips, and wax actuators, the pencil-thin Vease actuator, model 925100-01, operates without gears or converters. It incorporates a tightly wound, 8-turn helical spring made of the shape-memory nickel-titanium alloy Tinel®. The spring is attached to a lever arm and encased in a metal sleeve with an outer overload spring.

The actuator exerts a 1-pound force continuously throughout its stroke, eliminating the need for oversized actuators for maintaining full force at the end of the stroke. The device weighs 0.39 oz., giving it a high work-to-weight ratio. Jam and overload protection are built in; any load greater than 50 percent of the rated value is relieved automatically to protect the actuator and any components attached to it. The drive source can be AC or DC and need supply only the correct average current for a specified actuation time. Because it activates at just above normal ambient temperatures, it can be actuated thermally or electrically.

Shape-memory actuation starts and stops gently, minimizing vibration and high G movements. The device makes no noise during actuation or reset. It also contains no magnetic materials. Constructed of brass, plastic, and Tinel, it resists corrosion in most fluids.

For more information, contact: Dick Yaeger, Raychem Corporation, 300 Constitution Dr., Menlo Park, CA 94025-1164, telephone (415) 361-4719. Circle 65



Token-ring LAN Adapter Chip Set

Texas Instruments has introduced a token-ring local area network (LAN) adapter chip set, the TMS380. The set was developed jointly with IBM, and provides standardized interfaces for attaching computers, terminals, telecommunications equipment, and other information processing devices to the IBM Token-Ring Network.

The TMS380 meets the ANSI/IEEE Std 802.5-1985 specification and also the European Computer Manufacturers' Association 89 standard for token-ring, baseband local area networks. It was designed to meet LAN connection requirements of personal computers, advanced technology personal computers, and emerging 32-bit professional workstations. The chip set provides a 4 million bit/sec. data rate over already installed telephone twisted pair, shielded twisted pair, and fiber optics.

For more information, contact: Texas Instruments, Semiconductor Group (SC-512), PO Box 809066 Dallas, TX 75380-9066, telephone (800) 232-3200, ext. 700. Circle 66

Literature

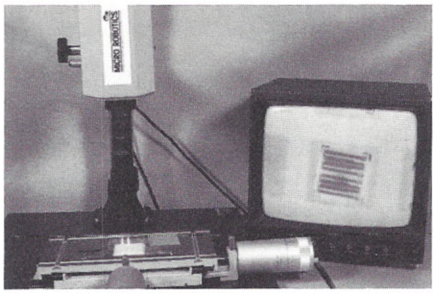
The following is a sampling of recent publications, marketing material, and technical literature.

- IEEE Computer Society Publications Catalog. Contact: IEE Computer Society, Dept. CN5, PO Box 80452, Worldway Postal Center, Los Angeles, CA 90080, telephone (800) CS-BOOKS. Circle 67
- *Artificial Intelligence: Bibliographic Summaries of the Select Literature, Volumes I, II.* Contact: The Report Store, 910 Massachusetts St., Suite 503, Lawrence, KS 66044, telephone (913) 842-7348. Circle 68
- *Smart Manager's Guide to Effective CAD Management.* Contact: CAD/CAM Publishing, Inc., 841 Turquoise St., Suite D, San Diego, CA 92109, telephone (619) 488-0533. Circle 69
- *Manufacturing Simulation: A New Tool for Robotics, FMS, and Industrial Process Design.* Contact: Technical Insights, Inc., PO Box 1304, Fort Lee, NJ 07024, telephone (201) 568-4744. Circle 70
- "Positioning Systems/Lasers, and Accessories." Contact: Aerotech, Inc., 101 Zeta Dr., Pittsburgh, PA 15238-2897, telephone (412) 963-7470. Circle 71
- *The Artificial Intelligence Directory, 1985 ed.* Contact: DM Data Inc., 6900 E. Camelback Rd., Suite 1000, Scottsdale, AZ 85251, telephone (602) 945-9620. Circle 72
- "AVA Machine Vision Glossary." Contact: Automated Vision Association, PO Box 1366, Dearborn, MI 48121, telephone (313) 271-7800. Circle 73
- *Integrated Manufacture* and *Flexible Manufacturing Systems.* Contact: Air Science Company, PO Box 143, Corning, NY 14830, telephone (607) 962-5591. Circle 74
- Catalog of publications on robotics, CAD/CAM/CAE, FMS, etc. Contact: Elsevier Science Publishing Co., Inc., PO Box 1663, Grand Central Station, New York, NY 10163. Circle 75
- *Journal of Robotic Systems.* Contact: Subscription Dept., John Wiley & Sons, Inc., 605 Third Ave., New York, NY 10157. Circle 76
- *Robotics Annual Patent Directory.* Contact: Communications Publishing Group, Inc., 1505 Commonwealth Ave., Suite 32, Boston, MA 02135, telephone (617) 787-0138. Circle 77

New Products

High Resolution Vision System

Micro Robotics Systems, Inc. is offering a new high resolution vision system for precision assembly and parts inspection. The system is adaptable to most assembly line operations that use robots for assembly, component insertion, chip and wafer handling, and PCB inspection. It can also be used as a standalone inspection system in operations such as silicon wafer processing and IC manufacturing.

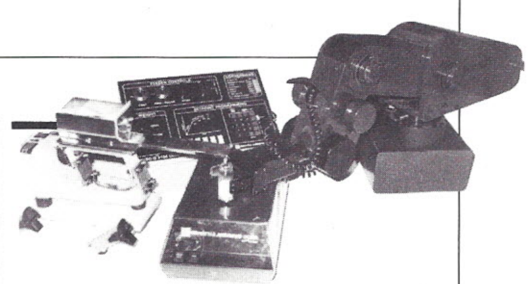


The system is available in three configurations. The basic system includes the Micro PDP-11 processor, a VT 220 high resolution graphics terminal, keyboard, camera, basic imager, and driver software; the second level adds on an ALU processor and software for high speed computing power to 1/30 of a second; and the third level includes all the above features plus an expanded memory and custom applications software.

The system houses up to six vision boards; the vision boards include three image frame buffers. Each frame buffer has a spatial resolution of 768 by 512. Pixels have an 8-bit depth, which corresponds to a broad gray scale of 256 different levels. Up to four input devices can be supported, and one input look-up table and three output look-up tables are included. The system features red, green, and pseudo-color generation with character overlay and pen and scroll capabilities.

For more information, contact: Micro Robotics Systems, Inc., 660 Suffolk St., Lowell, MA 01854, telephone (617) 937-1970.

Circle 78



Robotic Powder Dispenser

Hudson Robotics is offering a robotic workcell for dispensing precise quantities of powder automatically. The system uses a Mitsubishi RM-501 Movemaster robot interfaced to a Hierath and Andrews ISO-G powder dispenser. The robot has five axes of movement, a 2.7 lb. payload, and a speed of up to 15.7 in./sec. The workcell includes automatic loading/unloading of vials, cartridges, or other powder containers that might be required. Applications include the pharmaceutical, pyrotechnic, powedered metal, chemical, and ceramic industries.

For more information, contact: Thomas R. Jividen, Hudson Robotics Inc., 120 Morris Ave., Springfield, NJ 07081, telephone (201) 376-7400.

Circle 79

New Products

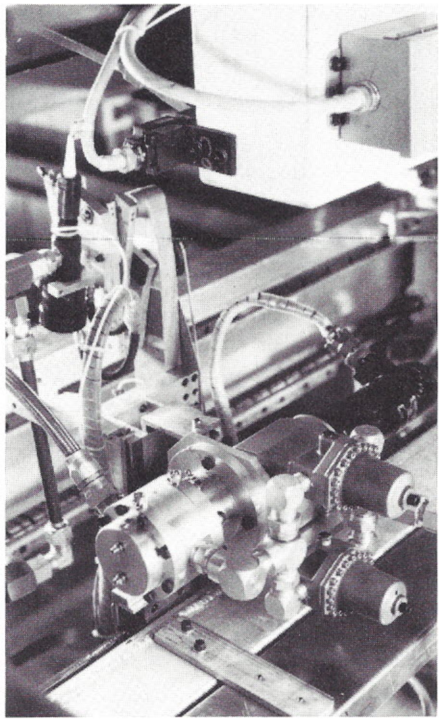
Sealant Application Control System

Robotics, Inc. has developed a flow control system said to reduce by more than 25 percent the time required for automatic dispensing of adhesives and sealants. Program-A-Flow™ allows an automated system to dispense a uniform bead of material over a complex path without having to maintain constant speed at the dispensing tip.

The system consists of a pump, speed reducer, electric motor, and tachometer mounted on a common base. When coupled to the controller of an automated dispensing system it allows the dispensing system to automatically vary material flow in response to programmed changes in system speed or to compensate for variations in material viscosity. The system can slow down for curves and accelerate to its maximum dispensing speed, while automatically varying flow rate to produce a uniform bead of sealant or adhesive.

For more information, contact: Marketing Manager, Robotics, Inc., RD 3–Rt. 9, Ballston Spa, NY 12020, telephone (518) 899-4211.

Circle 80



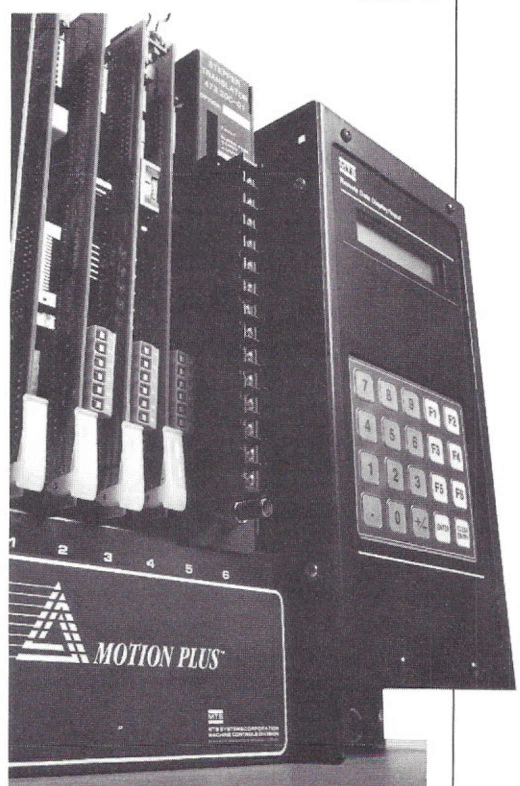
Multi-axis Motion Control

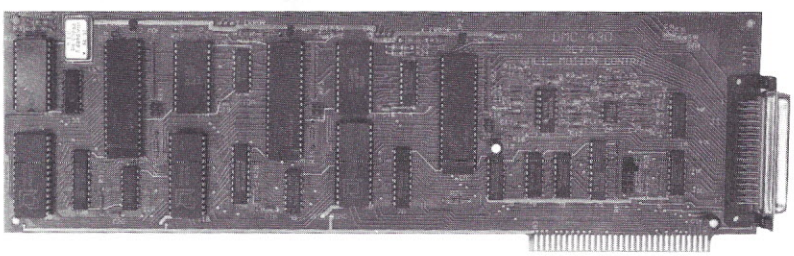
Motion Plus™, from MTS Systems Corporation, uses new distributed processor techniques to command higher-speed, more intricate multi-axis machine motions. Machine data and logic control are also included in the package, eliminating the need to interface separate controllers. The main 16-bit system processor that governs the Motion Plus activities includes an SBX expansion port for plug-in additions of such functions as analog I/O, additional communications protocols and channels, and mass data storage.

Each axis has its own microprocessor controlled command generator in which are stored up to 16 unique machine motion profiles. These run on command from the system processor, allowing it to perform other tasks. New profiles can be downloaded from the system processor at any time. Stored motion profiles can be run independently or in strings to satisfy a highly varying machine motion requirement.

For more information, contact: MTS Systems Corporation, PO Box 24012, Minneapolis, MN 55424, telephone (612) 937-4000.

Circle 82





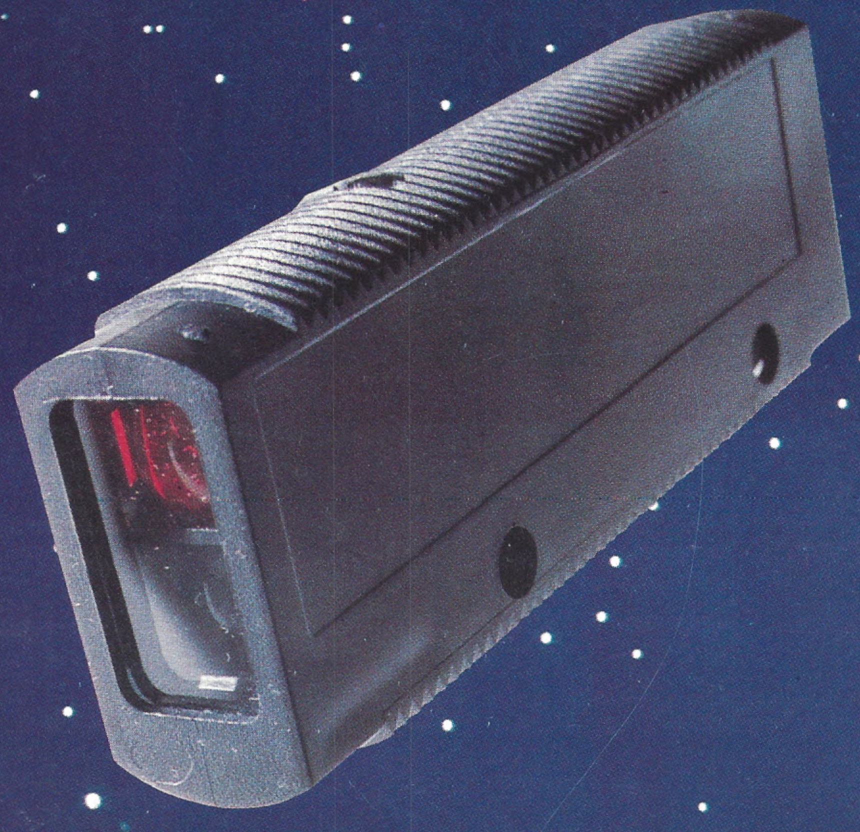
Three-Axis Motion Controller

Circle 81

Galil Motion Control has introduced the DMC-430, a three-axis programmable motion controller contained on an IBM PC compatible card. It can control the position and velocity of up to three DC or brushless DC motors. The microprocessor based DMC-430 governs all aspects of motor control including precision positioning, velocity profiling, and status reporting. It is completely programmable and parameters for desired motion profiles are downloaded directly from the IBM PC. Plugging directly into the IBM PC bus, the DMC-430 takes up only one card slot, saving the user I/O space and money.

The DMC-430 accepts position feedback from an incremental encoder. No tachometer feedback is required because the DMC-430 stabilizes the system with a digital filter that can be programmed for optimum motor response. With proper filtering and system mechanics, speed ranges of up to 30,000:1 and position resolutions less than 1 micron can be achieved. The DMC-430 interfaces to virtually any size DC motor and amplifier combination making the controller suitable for a wide range of multi-axis applications including factory automation, machine tools, robots, and manufacturing equipment.

For more information, contact: Lisa Wade, Marketing Manager, Galil Motion Control, Inc., 1928-A Old Middlefield Way, Mountain View, CA 94043, telephone (415) 964-6494.



Photoswitch introduces a new dimension in photoelectric sensing.

The first thing to notice about the new PHOTOSWITCH Series 6000 mini-sized self-contained controls is the size and shape. These controls have flat sides and round, threaded edges. They can be mounted side-by-side or fitted into a 1″ diameter hole.

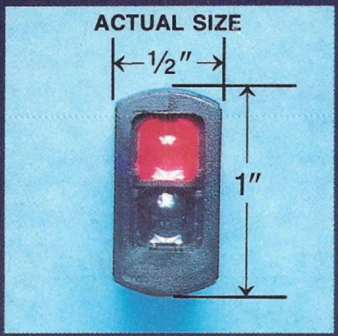
Series 6000 controls are small and operate in the tightest spaces. Yet, they deliver sensing distances that are the best in the industry—for retroreflective scanning, to 20 feet with plenty of operating margin.

A visible LED beam plus an alignment and output indicator simplifies installation and inspection. Externally adjustable sensitivity on all models provides flexibility for difficult applications, such as detecting small or transparent objects. AC and DC versions interface directly with programmable controllers, solid-state logic or power loads.

PHOTOSWITCH Series 6000 controls are completely encapsulated and sealed in a high-impact, corrosion-resistant Nema 4 watertight housing. All models have UL Recognized cable, eliminating the need for conduit. This significantly reduces installation costs.

PHOTOSWITCH offers over 50 models of the mini-sized Series 6000 controls to provide retroreflective, proximity, transmitted beam, converging beam and fiber-optic versions. Including the only available mini-sized "Polarized Beam" retroreflective controls which eliminate false signals from highly reflective material.

For more information about the new dimension in photoelectric sensing from the leading producer of industrial photoelectric controls, please contact your nearest PHOTOSWITCH distributor, local PHOTOSWITCH sales office or **Electronics Corporation of America, PHOTOSWITCH Division, 265 Winter Street, Waltham, Massachusetts 02154. (617) 466-8000.**



PHOTOSWITCH®

Better automation in one word

Circle 52